TECHNICAL REPORT ECOM-2558

TESTING OF DIGITAL DATA TRANSMISSION SYSTEMS

BY

JAMES E. BARTOW

FEBRUARY 1965

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH

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COMMUNICATIONS DEPARTMENT

February 1965

DA Task No. 1E6 41209 D535 12

ABSTRACT

This report describes tests performed on various communication systems to determine their capability to pass digital data. A collection of test results from many sources has been gathered. Experiments on HF, VHF, UHF and SHF radios, and on cable and wire systems, etc., are included. Preliminary results of several experimental programs which have not been published previously are presented. An analysis of the data is made. The significance of the results in terms of specifying and designing a communication channel to optimize its inter-operation with a data processing system is explained. An outline is presented of further tests required to determine basic communication limitations, to discover causes of digital errors, and to verify specific data/communication system performance.

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I. INTRODUCTION

Present communication systems are generally designed to transmit analog signals over a nominally 3 kc or 4 kc voice channel. These systems have been and will be called upon to support increasing quantities of digital data. The degree to which these systems fulfill this need has been the subject of numerous investigations.

II. PURPOSE

The purpose of this report is to present the results of testing of digital data transmission systems, to discuss the nature and significance of error rates and distributions, and to describe planned and proposed future tests.

III. DISCUSSION

A. Results of Tests

1. Seventh Army Tests, Spring 1964

a. Tests were made[1] at a bit rate of 1200 bits/sec. between Army main and Army rear as well as Army main and the two Corps, on both garrison and field circuits. The circuits were usable for testing a total of 1,906 minutes. 1,776 minutes (or 93% of these minute intervals) were error free.

b. The number of modulation-demodulations between Army and Corps was limited to three and in most cases was two. The highest and lowest frequency channels of the FDM multiplexers were avoided because of possible excessive differential delay distortion. During all measurements, the channel signal-to-noise ratio exceeded 25 db; the average value was 30 db.

c. The major cause of errors seemed to be crosstalk. It was found necessary to patch the data signals around patch panels and junction boxes where pick-up from d.c. teletype, loud talkers, etc. interferred with the data.

d. The FDM carrier equipment is designed to accept speech with no more than 25% loading. As an increasing number of channels are allocated to data and other sources of continuous signals, more care must be taken to adjust input levels. Excessive overload of common amplifiers causes intermodulation distortion, crosstalk, and digital errors.

e. The conclusion reached as a result of these tests was that the communication channels, as provided between Army and Corps, are satisfactory for data transmission provided the previously mentioned precautions are taken.

2. Seventh Army Tests, Fall 1964

a. In the Fall of 1964 the CCIS-70 Data Transmission Test and Evaluation Team conducted tests in Europe on digital data transmission through several Seventh Army radio communication links [2]. The tests were performed during the Seventh Army Fall exercises (FALLEX).

b. The team's mission was to determine the capability of the circuits, which were composed of existing equipments, to transmit and receive digitized data in a field environment. The circuits used typified three types of systems: The command system, the area system and the garrison system. In each system data was transmitted through the center channels of its FDM multiplexers to minimize errors due to delay distortion. Each system used AN/TRC-24's and AN/GRC-50's as radio links between multichannel telephone equipment.

c. The area system contained 10 modulation - demodulation points, whereas the command and garrison systems were limited to not more than four each. The S/N ratios ranged from 17 to 50 db. Much of the circuit outage time was caused by "looping back from intermediate points". In most instances the point of looping back could be determined but its cause could not be. To avoid the problem, work was continued on another channel. Lack of time and personnel precluded a thorough investigation of the problem.

d. At times sustained error bursts caused error rates considerably greater than one error in 10^5. In these cases, the data rate was lowered until an acceptable error rate was obtained. A majority of the errors were produced by error bursts. Transmissions were relatively free of errors when bursts were absent.

e. The tables that follow * depict the various error rates for the transmission speeds applied for both the PSK and FSK modems used. Restricted test time limited operation to only 1200 bits per second in the garrison system.

f. The test team concluded that additional tests should be performed to determine the causes of the looping back of data and the causes of error bursts.

* (Tables I, II and III)

TABLE I

DATA TRANSMISSION TESTS OVER COMMAND COMMUNICATION SYSTEM

SEVENTH ARMY - FALLEX

Modem	Data Rate Bits Per Seconds	Total Number of Runs	Usable Number of Runs	Bits Trans-mitted	Errors	Error Rate
PSK	1200	68	35	103.15×10^6	5229	4×10^{-5}
FSK	1200	5	3	$.648 \times 10^6$	88	2.9×10^{-5}
PSK	600	6	3	$.468 \times 10^6$	686	15×10^{-5}
FSK	600	4	1	$.252 \times 10^6$	42	17×10^{-5}
FSK	75	10	3	$.1523 \times 10^6$	54	3.6×10^{-5}

PSK - Four Phase Modulation

TABLE II

DATA TRANSMISSION TESTS OVER AREA COMMUNICATION SYSTEM

SEVENTH ARMY - FALLEX

Modem	Data Rate Bits Per Second	Total Number of Runs	Usable Number of Runs	Bits Transmitted	Errors	Error Rate
PSK	1200	6	2	8.64×10^{6}	332	3.8×10^{-5}
FSK	1200	3	2	8.64×10^{6}	96	1.1×10^{-5}
PSK	600	5	2	1.98×10^{6}	12	$.6 \times 10^{-5}$
FSK	75	4	3	$.71 \times 10^{4}$	0	0

PSK - Four Phase Modulation

TABLE III

DATA TRANSMISSION TESTS OVER GARISON COMMUNICATION SYSTEM

SEVENTH ARMY - FALLEX

Modem	Data Rate Bits Per Second	Total Number of Runs	Usable Number of Runs	Bits Trans-mitted	Errors	Error Rate
PSK	1200	47	10	28.7×10^6	1429	5×10^{-5}

PSK - Four Phase Modulation

3. AN/VRC-12 Tests Performed at USAEL

a. Data transmission tests have been performed in the vicinity of USAEL [3] with the AN/VRC-12. Tests were performed at 41.5 mc, over paths of from 3 to 10 miles at bit rates of 300, 600 and 1200 bits/sec. Tables IV, V and VI present the results. The spread of the results is shown in Figures 1 and 2.

b. Each test run was of approximately 200 seconds duration and each was repeated on several days. The results are presented both in terms of the average error rate and in terms of error-free seconds. The percent of error free seconds is indicative of the percent of one-second messages that would be received error free. While the average error rate was often greater than one error in 10^5 bits, in most of the runs 95% or more of the messages would have been received error free. The major source of errors was ignition noise from trucks passing in vicinity of the receiver. During periods without truck traffic. transmissions up to 10 miles were substantially error free.

TABLE IV

AN/VRC-12 FIELD TEST RESULTS AT 1200 BPS

Distance (Miles)	Data Modem Used	Bits Transmitted	Bits In Error	Average Bit Error Rate	Total Time (Sec)	Error Free Sec	% of Sec Error Free
3.0	IBM	720,000	0	-	600	600	100%
3.0	TYC-1	735,600	26	3.54×10^{-5}	613	590	92%
4.8	TYC-1	906,000	64	7.06×10^{-5}	755	736	97.5%
4.8	IBM	960,000	0	-	800	800	100%
9.2	IBM	1,132,800	715	6.31×10^{-4}	944	860	91%
9.2	TYC-1	1,156,800	186	1.61×10^{-3}	964	656	63%
10.3	IBM	1,322,400	141	1.06×10^{-4}	1102	1071	97%
10.3	TYC-1	1,426,800	575	4.04×10^{-4}	1189	963	81%
19.0	TYC-1	856,800	9,628	1.12×10^{-2}	714	27	3.8%
Summary		9,227,200	13,009	14.09×10^{-4}	7628	6303	83%

TABLE V

AN/VRC-12 FIELD TEST RESULTS AT 600 BPS

Distance (Miles)	Data Modem Used	Bits Transmitted	Bits In Error	Average Bit Error Rate	Total Time (Sec)	Error Free Sec	% of Sec Error Free
3.0	IBM	340,200	0	-	567	567	100%
3.0	TYC-1	356.400	0	-	594	594	100%
4.8	IBM	500,400	12	2.40×10^{-5}	834	830	99.5%
4.8	TYC-1	519,000	0	-	865	865	100%
9.2	IBM	431,400	109	2.53×10^{-4}	719	690	96%
9.2	TYC-1	501,600	191	3.82×10^{-4}	836	773	92.5%
10.3	TYC-1	625,800	164	2.62×10^{-4}	1043	1013	97%
10.3	IBM	710,400	53	7.45×10^{-5}	1184	1162	98%
19.0	TYC-1	361,200	736	2.04×10^{-3}	602	438	72.7%
Summary		4,346,400	1,265	2.91×10^{-4}	7244	6932	96%

TABLE VI

AN/VRC-12 FIELD TEST RESULTS AT 300 BPS

Distance (Miles)	Data Modem Used	Bits Transmitted	Bits In Error	Average Bit Error Rate	Total Time (Sec)	Error Free Sec	% of Sec Error Free
3.0	IBM	97,200	0	-	324	324	100%
3.0	TYC-1	180,000	0	-	600	600	100%
4.8	IBM	239,700	0	-	799	799	100%
4.8	TYC-1	300,000	0	-	1000	1000	100%
9.2	IBM	189,000	445	2.35×10^{-3}	630	401	63.5%
9.2	TYC-1	247,200	53	2.15×10^{-4}	824	812	98.5%
10.3	IBM	322,200	64	1.99×10^{-4}	1074	1032	96%
10.3	TYC-1	329,100	105	3.19×10^{-4}	1097	1052	96%
Summary		1,904,400	667	3.52×10^{-5}	6348	6020	95%

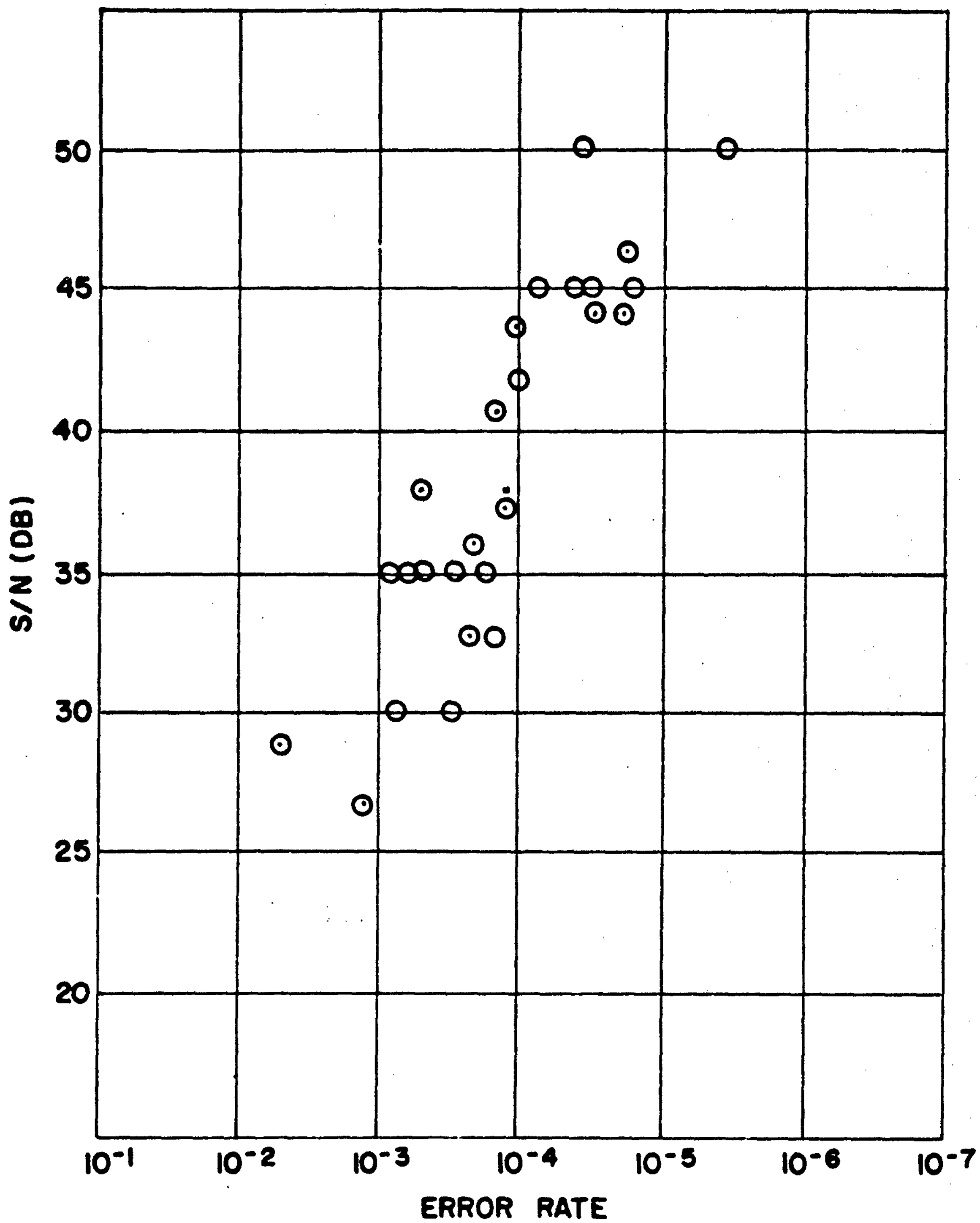


FIG. 1 ERROR RATE VS AN/TYC-1 (XC-2), 1200 BPS

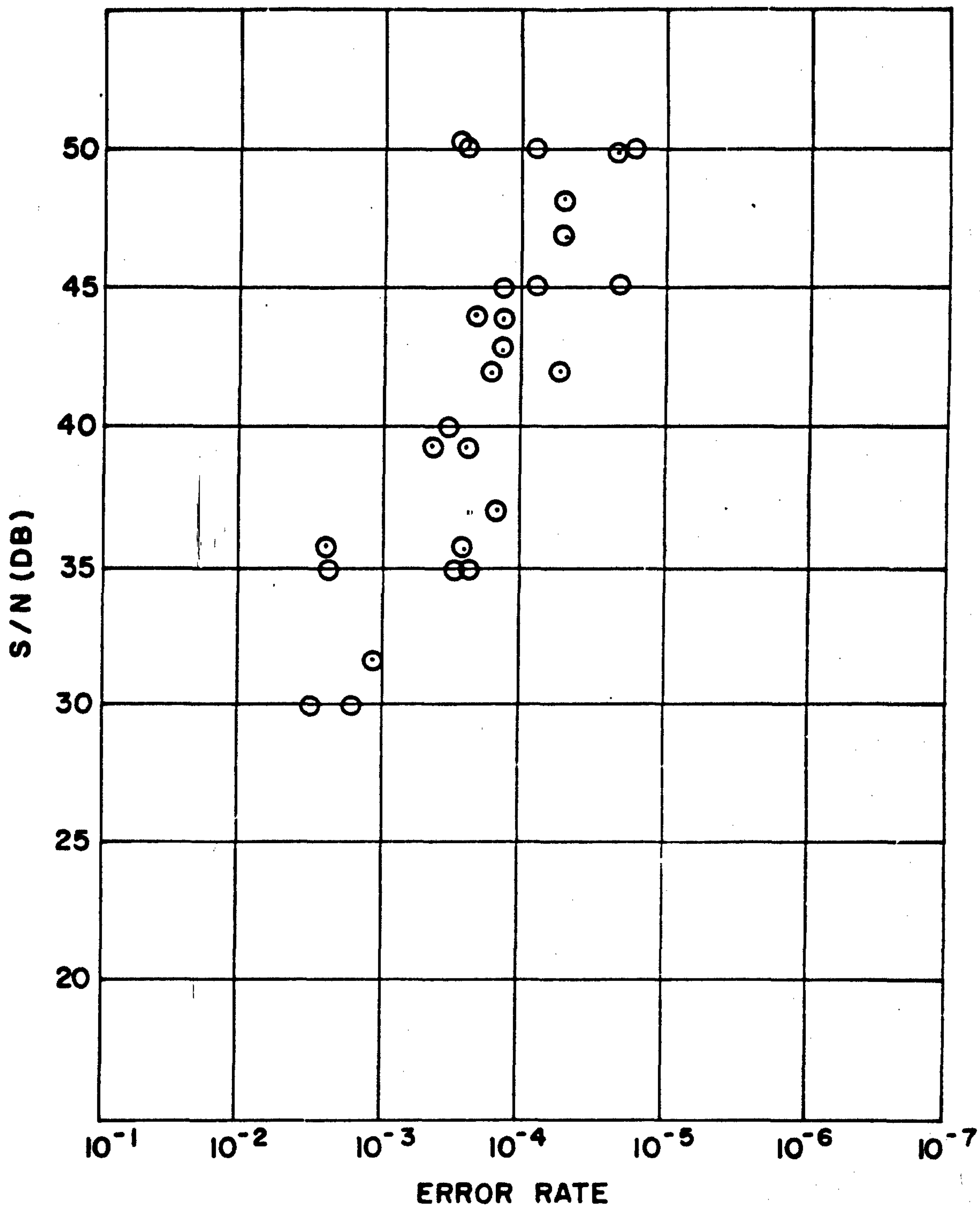


FIG.2 ERROR RATE VS S/N DI-PHASE MODEM, 600 BPS

4. AN/VRC-12 Tests Performed at USAEPG.

a. Data transmission tests were performed by Bunker Ramo with the AN/VRC-12 Radio Set using a vestigial sideband modulated data terminal (the Sebit-24 Data Modem) [4]. Tests were performed at 5, 12 and 19 miles at bit rates of 600, 1200 and 2400 bits per second. A summary of the results of these tests is given in Table VII, on the following page.

TABLE VII

AN/VRC-12 TESTS BY BUNKER - RAMO

Distance (Miles)	Data Rate (Bits/Sec)	Number of Runs	Total Bits Transmitted	Average Error Rate
19	600	7	7.45×10^6	2.96×10^{-4}
19	2400	5	33.43×10^6	1.48×10^{-5}
12	600	9	8.81×10^6	1.5×10^{-4}
12	1200	3	5.25×10^6	4.3×10^{-4}
12	2400	12	38.63×10^6	1.7×10^{-4}
5	600	21	9.223×10^6	2.5×10^{-4}
5	1200	10	10.216×10^6	1.6×10^{-4}
5	2400	20	30.58×10^6	1.8×10^{-4}

5. AN/PRC-25 Tests at USAEPG [5].

a. Tests were performed at USAEPG to determine the feasibility of using Radio Set AN/PRC-25 to transmit digital data as required for the Fire Support System of CCIS-70.

b. The phase 1 tests were performed over a line-of-sight path of 15.5 km using a Message Entry Device (MED). A total of 70 MED messages were transmitted on 3 r-f frequencies at a rate of 75 bits per second. The total number of FIELDATA characters transmitted was 1890. All messages were received free of errors. Another run of 20 messages were transmitted over the same path but from non-line-of-sight positions. No errors were found in the received messages.

c. The phase 2 tests were performed under similar conditions over a different 15 km path. A total of 30 FADU messages (32 FIELDATA Characters) were transmitted. No errors were found in the received messages. Another run, at 24 km, of 1920 FIELDATA characters, was made. Again, no errors were received.

d. The phase 3 tests were performed at 1200 bits/second, at 15 km, line-of-sight. Radio Set AN/VRC-12 was used for the purpose of comparison. During a typical series of tests (2310 FIELDATA characters each) the AN/VRC-12 tests were error free for three runs, while errors occurred in the received messages from the AN/PRC-25 during three of four runs. It was concluded that the AN/PRC-25 is not suitable for the transmission of 1200 bits/sec. over 15 km paths.

6. UNICOM Tropospheric Scatter Tests [6].

a. Tests were performed over a 93 mile tropospheric scatter circuit from Fort Monmouth, New Jersey to Tobyhanna, Pennsylvania. The transmitter power output is 1 kw. The horn-fed parabolic reflectors are 15 feet in diameter. The dual space-diversity receivers are preceded by parametric amplifiers. The f-m transmissions are made at a frequency of 4.8 gc/s.

b. A pseudo-random pulse stream at a rate of 652,800 bits per second, converted to a trinary signal, frequency modulates the transmitter. The receiver output is compared, bit by bit, with a stream generated at the receiver location which is identical to the transmitted stream. A counter records each error and displays the total number of errors over a given period. Usually one minute intervals are used. Many of these one minute averages are tabulated throughout the day and curves of cumulative distribution of error rate vs percentage of time is plotted. Such a plot is shown in Figure 3, on the following page.

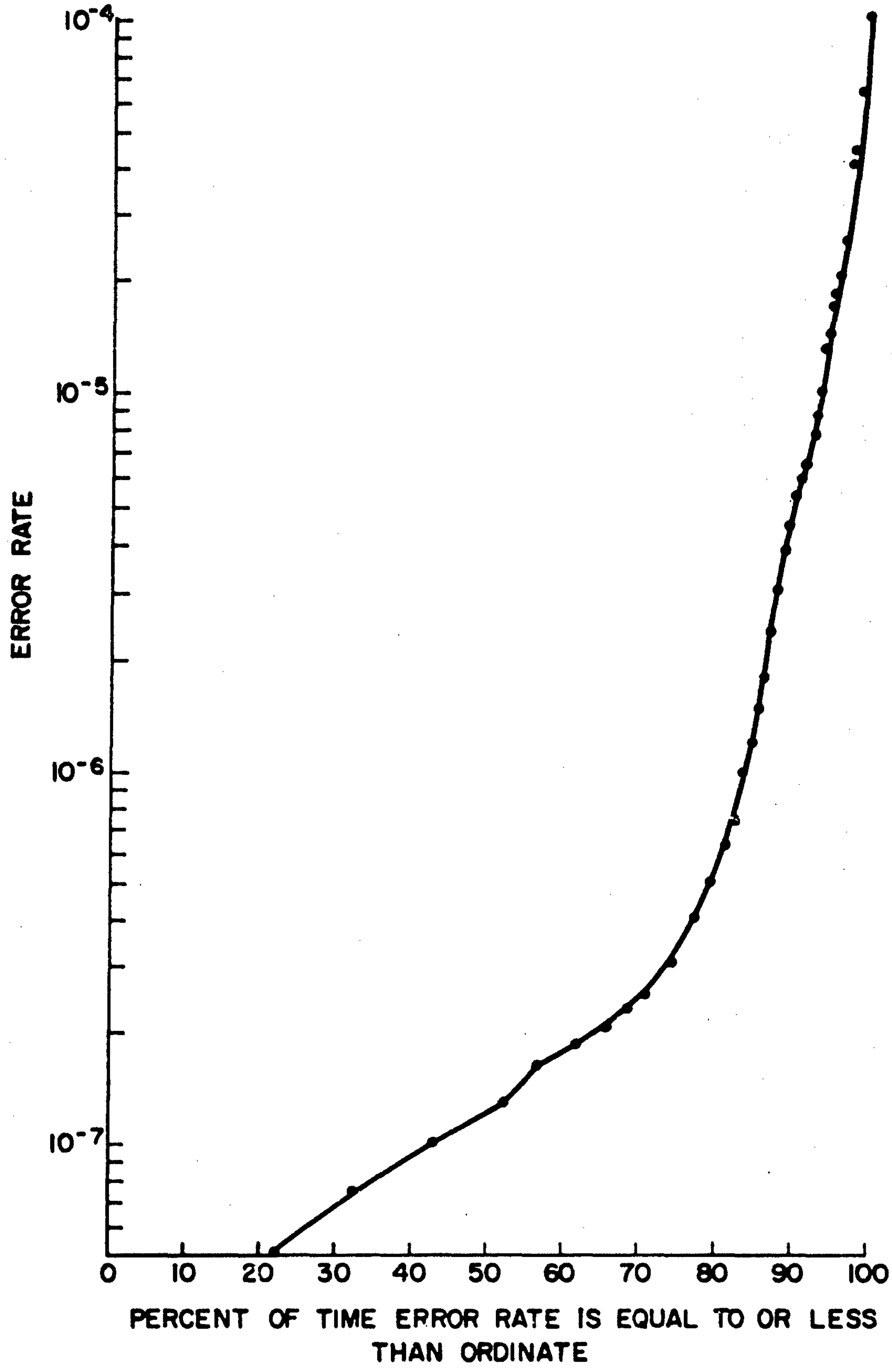


FIG. 3 DECEMBER 10 1964 9 HR PERIOD READINGS IN MINUTE INTERVALS

7. AN/TCC-7 Field Tests [7].

a. Tests were performed on two Telephone Terminals AN/TCC-7 interconnected with 80.5 miles of spiral-four cable (Cable Assembly CX-1065/G), 12 unattended Telephone Repeaters AN/TCC-11 (spaced at 5 3/4 mile intervals) and a single AN/TCC-8 Telephone Repeater (attended). The data modems used were the AN/TYC-1 (FSK), the IBM (di-phase) and the Hughes HC-270 (quaternary phase shift). The data rates were 300, 600, 1200 and 2400 bits per second. The channels of the 12-channel FDM multiplex were connected in tandem giving combinations of from three to ten tandem channels.

b. The larger error rates occurred when the AN/TCC-7 required alignment. In one case a thunderstorm caused an increase in errrors. The results are summarized in Table VIII.

c. It can be seen that one second messages would be transmitted error free more than 99% of the time in all but one case. The average bit error rates are presented, but are considered less significant than the percentage of error free seconds.

TABLE VIII

AN/TCC-7 FIELD TESTS

Data Modem	Bit Rate	Total Sec	Sec With Errors	% of Sec Error Free	Total Errors	Nr of Tandem Channels	Average Bit Error Rate	Delay Eq
IBM	1200	82,000	94	99.8%	106	10	$1.08X10^{-6}$	No
IBM	1200	57,000	85	99.6%	236	6	$3.45X10^{-5}$	No
IBM	1200	203,816	452	99.6%	1532	3	$6.25X10^{-6}$	No
TYC-1	1200	19,000	328	98%	342	10	$1.50X10^{-5}$	Yes
TYC-1	1200	26,000	164	99%	442	6	$1.92X10^{-5}$	Yes
TYC-1	1200	93,029	119	99.8%	200	4	$1.78X10^{-5}$	Yes
HC-270	1200	152,000	18	99.9%	63	10	$3.46X10^{-6}$	No
HC-270	2400	55,000	15	99.8%	50	4	$3.78X10^{-7}$	Yes

8. European Telephone System Tests[8].

a. Line noise on commercial telephone circuits was measured and found to be essentially different from white noise. It is partially caused by crosstalk, power interference, line scratches, hum, clicks, etc. The most important source of this noise is modulation caused by selector contact vibrations resulting from the step-by-step motion of adjacent selector groups. This last type consists of bursts of pulses with large amplitudes separated by periods of relatively low noise.

b. A total of 14 hours of recordings was made during main business hours. The telephone circuit was dialed up, and the telephone sets replaced by 600 ohm resistors. The hand set acoustical noise was thus avoided. The tape recorder was connected at the main distribution frame located at the telephone exchange. By dividing time into intervals (up to a maximum of .32 seconds) the frequency of spikes in those intervals exceeding an adjustable threshold was determined. This data is presented in Figure 4.

c. Data was transmitted over a simulated circuit at a bit rate of 1800 bits per second. If the maximum attenuation admitted by the Deutsche Bundespost is present, the high noise levels interfere with the low data signal level and cause high error rates. The variations in allowable data transmitter power output (12 db) and attenuation (16 db) were simulated, and the recorded noise introduced into the data receiver. The results are seen in Figures 5 and 6.

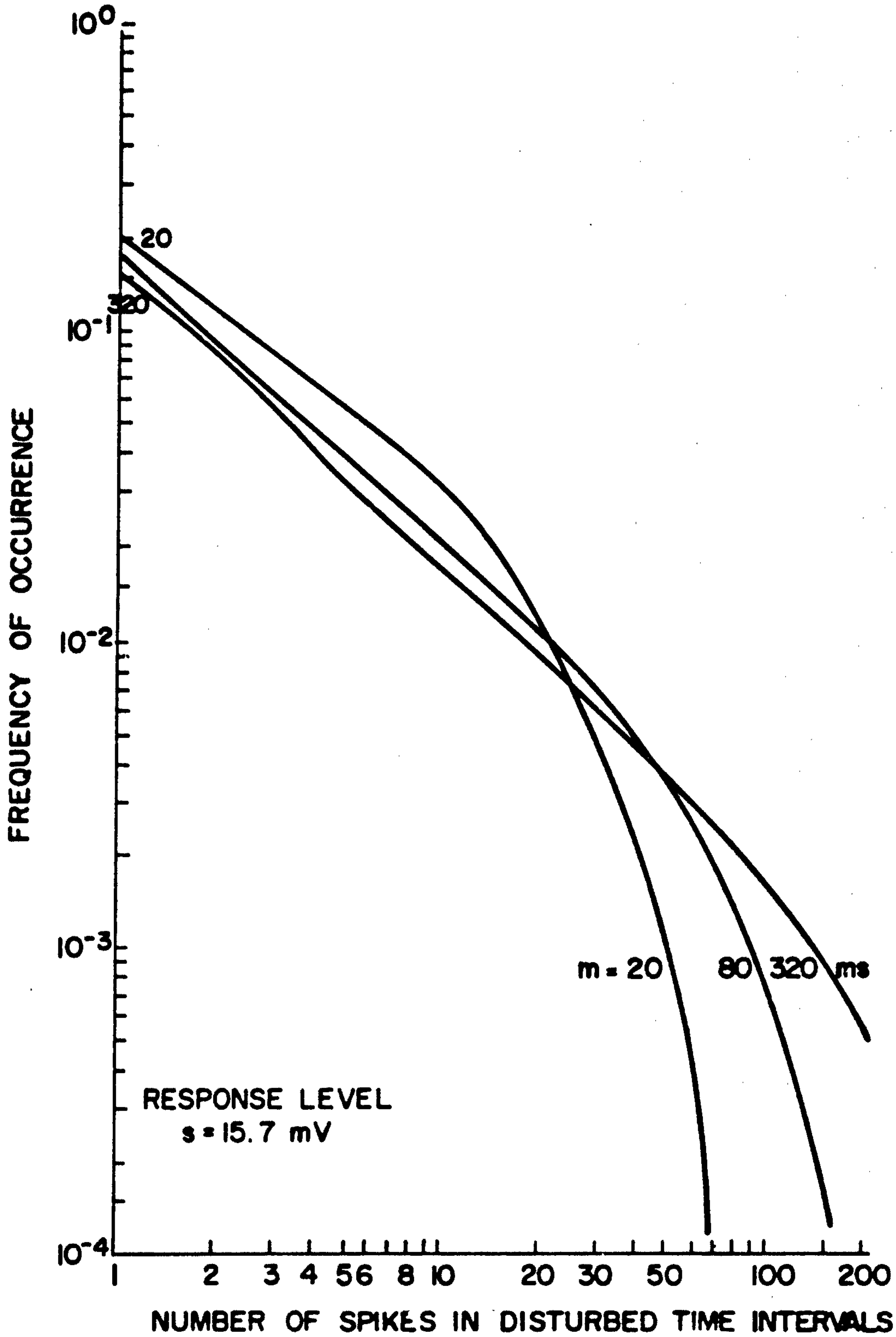


FIG. 4 FREQUENCY OF OCCURRENCE OF SPIKES IN DISTURBED TIME INTERVALS OF THE LENGTH m

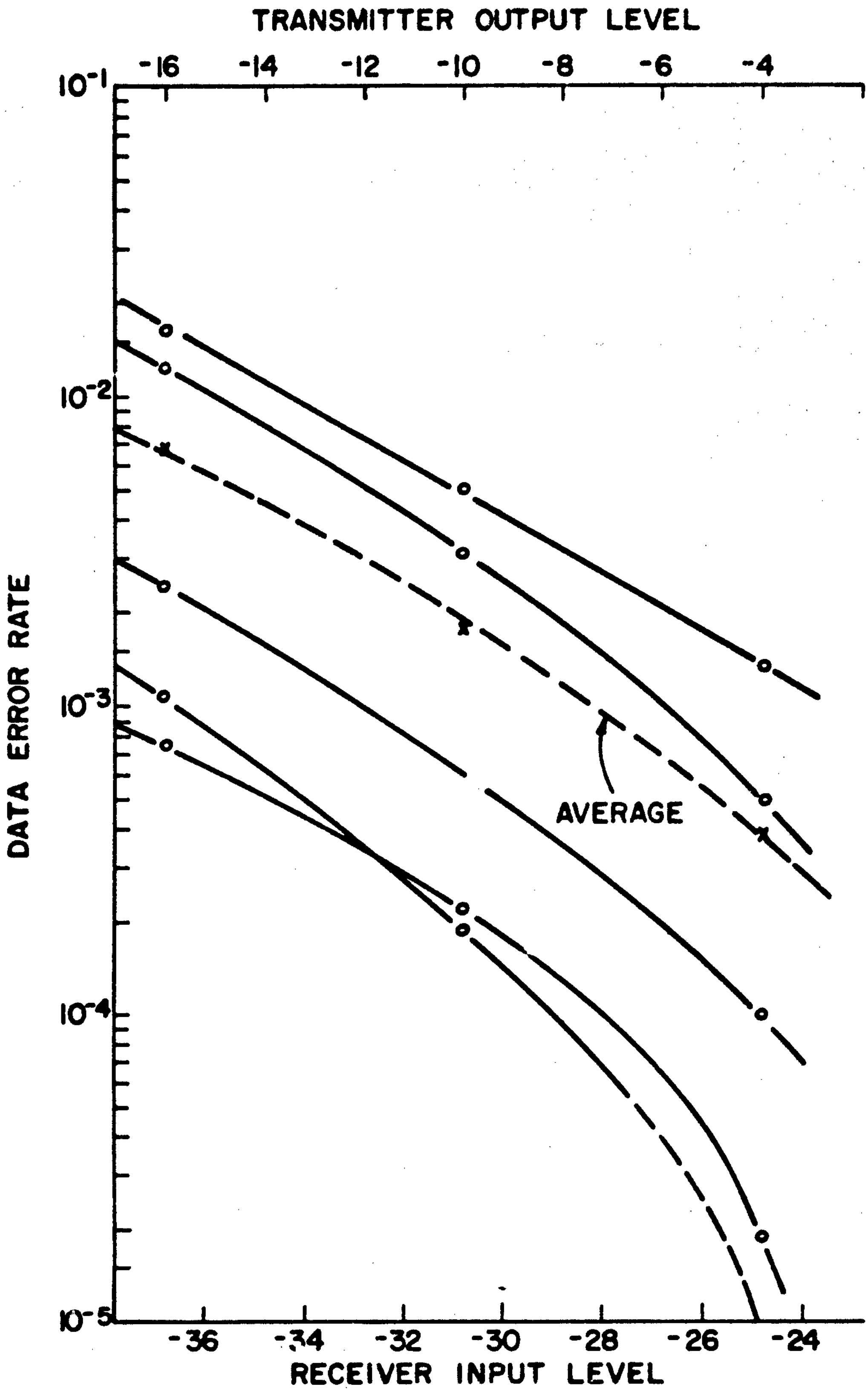


FIG. 5 DATA ERROR RATE OF SEVERAL NOISE TAPES

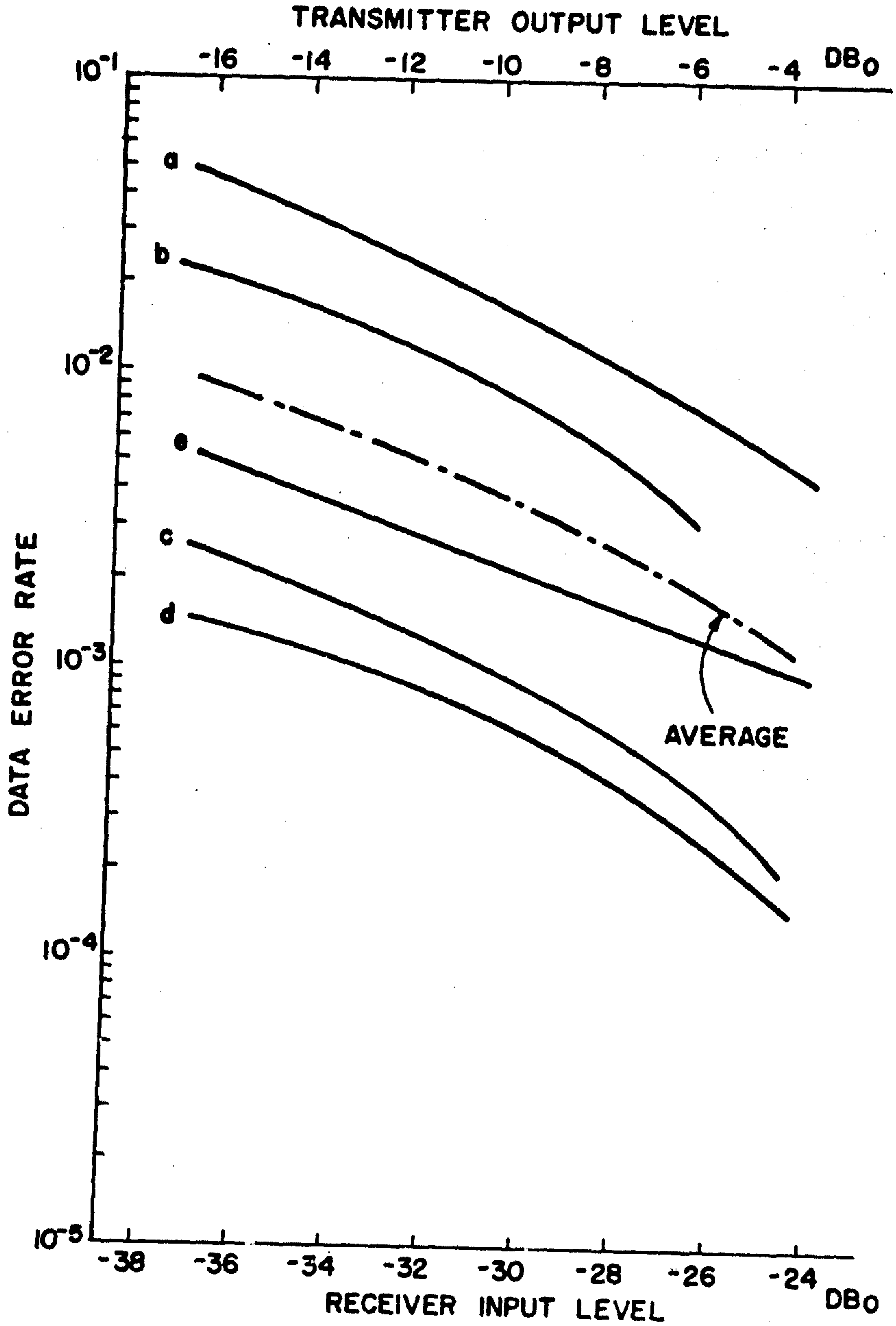


FIG. 6 DATA ERROR RATE (AM) OF SEVERAL NOISE LAPSES

d. In their testing of dialled-up toll circuits in the European area, Melas and Hopner[9] found that the error rates were higher in lines connected to exchange with rotary (Strowger) switches; a cross-bar switch or Ericsson exchange can improve the error rate by several orders of magnitude.

e. During several test connections in most European countries a series of pulses were sent through the line every 3 or 6 minutes by the PTT for toll metering purposes. Those pulses caused several hundred errors at every occurrence, until it was found that the interference could be completely eliminated by inserting a high-pass filter with a 500 cps cut-off at the receiver input.

f. The following results are reported:

(1)

Total time:	3 hrs. 16 mins.
Number of bits:	11.76×10^6
Number of errors:	897
Number of bursts:	445
% of bursts:	
(a) Single errors:	56
(b) Double errors:	13.6
(c) Triple errors:	7.3

(2)

		Blocks of 500 bits	Blocks of 63 bits
Number of blocks		23.5×10^3	186.4×10^3
% of blocks containing errors		1.87	0.644
% of	one single error	31.1	51.5
above blocks	one SE or DE	40.0	64.1
with only:	one SE, DE or TE	44.5	70.4

9. Hawaiian Submarine Cable Tests

a. The SAGE A-1 digital data transmission system was tested over a 5,000 mile loop circuit using the Hawaiian cable[10]. Thirty-six full duplex nominally 4 kc voice channels were available on each of two cables. Channel 5 (99 kc) was used in each direction. The channel frequency response was within 2 db of flatness from 200 to 3,000 cycles. The delay varied from 12.5 milliseconds at 300 cycles to 8.5 milliseconds at 1,800 cycles. Data was transmitted at a rate of 1,300 bits per second, 16 bits per character. The average signal-to-noise ratio was 28 db. Table IX presents the results.

b. The circuit was error-free for periods of up to 72 hours. Four days in which errors resulted from interruptions or circuit outages resulting from human or equipment failures are included; the "grand" averages are calculated both with and without these days. The average error rate was 3.55×10^{-6}; excluding the four days, it was 1.4×10^{-7} which is about 15 bits in error per day.

TABLE IX

POINT ARENA 1959

Date	Operating Time (Hours)	Error Rate Words in Error Per Minute	Error Rate Bits in Error Per 10^5 Transmitted	Average Nr. of Bits in Error in a Word in Error
18-19 Aug	24	3.5×10^{-3}	5.3×10^{-3}	1.2
19-20 Aug	23	8.7×10^{-3}	1.9×10^{-2}	1.73
20-21 Aug	22.75	0	0	
21-22 Aug	23	1.5×10^{-3}	5.6×10^{-3}	3.0
22-23 Aug	19.5	0	0	
23-24 Aug	22	0	0	
24-25 Aug	22.92	.36	.5	1.08
25-26 Aug	23	1.5×10^{-3}	1.9×10^{-3}	1.0
26-27 Aug	23	6.5×10^{-3}	8.4×10^{-3}	1.0
27-28 Aug	23	1.5×10^{-3}	1.9×10^{-3}	1.0
28-29 Aug	23	0	0	
29-30 Aug	23	7.3×10^{-4}	5.6×10^{-3}	6.0
31 Aug - 1 Sept	23.78	.017	.065	3.0
1-2 Sept	23	.02	.035	1.33
3-4 Sept	24	7.0×10^{-4}	9.1×10^{-4}	1.0
4-5 Sept	23	.135	.21	1.2
5-6 Sept	23	4.4×10^{-3}	1.7×10^{-2}	3.0
6-7 Sept	23.5	.151	.42	2.16
7-8 Sept	23	2.2×10^{-3}	2.8×10^{-3}	1.0
8-9 Sept	23	.018	.023	1.0
9-10 Sept	23	7.3×10^{-4}	3.7×10^{-3}	4.0

TABLE IX (Cont)

POINT ARENA 1959

Date	Operating Time (Hours)	Error Rate Words in Error Per Minute	Error Rate Bits in Error Per 10^5 Transmitted	Average Nr. of Bits in Error in a Word in Error
10-11 Sept	23	5.8×10^{-3}	3.1×10^{-2}	4.1
11-12 Sept	23	.81	8.6	8.3
12-13 Sept	23	7.3×10^{-4}	2.8×10^{-3}	3.0
13-14 Sept	24.25	7.6×10^{-3}	1.3×10^{-2}	1.36
14-15 Sept	23	5.8×10^{-3}	3.5×10^{-2}	4.75
15-16 Sept	23	3.5×10^{-3}	5.6×10^{-3}	1.2
16-17 Sept	20.16	5.8×10^{-3}	8.7×10^{-3}	1.17
Total	663.9			
Grand Average		0.056	0.355	3.78
Grand Average excluding 8/24-8/25 9/4-9/5 9/6-9/7 9/11-9/12		0.007	0.014	2.75

10. H-44 Cable - AN/GSC-4 Tests [11].

a. Digital Communication Set AN/GSC-4 transmits binary data by means of phase modulating a set of frequency multiplexed tones. It accepts and synchronously regenerates up to 5,400 bits per second of serial data. The equipment is designed to operate with a channel bandwidth of at least 3 kc and a signal-to-noise ratio of 28 db or greater.

b. Operating over 530 miles of H-44 cable at 5,400 bits per second, an error rate of 10^{-5} was obtained. The tests were of short duration (about 4 hours each). Additional data is required to verify the results.

c. In the Lincoln Laboratory tests referenced in paragraph 9, the Kingston - Canaveral tests used K, L and C carrier and H-44 cable and the Lexington - South Truro tests used H-44 cable.

d. Pfeiffer and Yudkin [12] report that the noise on an H-44 circuit appeared to fall into 4 categories according to the shape of the noise pulses:

Type I: Characterized by a doublet. The first impulse was of approximately 1 to 2 milliseconds in duration. The second, an impulse of opposite polarity and approximately 8 to 12 milliseconds in duration. Only 10% of this type of impulse was found to occur in multiple bursts (i.e., more than one of them on the same 1 second record).

Type II: Characterized by a single pulse of approximately 1 millisecond duration. It was found that 75% of these pulses occurred on the same record.

Type III: Characterized by one or two closely allied bursts of noise more or less evenly distributed throughout a 20 to 60 millisecond period (i.e., approximately 100 bits long at 2,400 bits). These pulses are the result of "ringing" the equivalent tuned circuit which comprises the telephone line by the disturbing impulse energy. Since the ringing period is relatively long, if the disturbing pulse is short (say 1 millisecond), the disturbances due to the leading and trailing edges of the disturbing pulse will tend to run together into a single noisy burst. If the leading and trailing edges of the disturbing pulse are sufficiently separated (say 30 milliseconds), then these will separately ring the telephone line and will appear as separate. but closely spaced, noise bursts. These types of impulses had a 50% probability of a multiple record.

Type IV: A final type of "impulse" was depicted in this article and it was indicated that these were not of a distinctive pulse shape. (The ones shown appeared to have a strong single-frequency component). These impulses had a 30% probability of a multiple record.

e. A "record" in the above terminology is a tape recording of the noise from approximately 0.3 seconds before to 0.9 seconds after the beginning of a noise pulse. The trigger level was maintained at 40 millivolts (i.e., -25.5 dbm). Although the records were maintained around the clock, it was found that 96% of the records occurred within the working day.

f. It was found that lengthy "quiet" intervals were usual, these interspersed by periods in which groups of pulses were recorded. A definite indication was found that the record following the previous record would have a high probability of being of the same type. A definite correlation between thunderstorm activity and records was observed, but by no means accounted for more than a relatively small proportion of the records.

11. Coaxial Cable, L-3 Carrier Tests.

a. The Milgo Digital Data System was tested over looped L-3 carrier on a coaxial cable telephone circuit from Miami, Florida to Charlotte, North Carolina, a total length of 1,678 miles [13]. The data rate was 1,000 bits/sec. (with 16 bits per word) during the test. The receive level was normally expected to be -8.5 dbm. During the test the receive level varied widely and dropped as low as -17.5 dbm. The average noise level was of the order of -40.0 dbm or better, so background noise was not an important factor in data errors. The average bit error rate for the test was 8.8×10^{-6}. During 5 days, the error rate was less than 10^{-7}. The circuit was error-free for 24 hours on some occasions and inoperable during a finite interval at other times. The error rates for specific intervals are shown in Table X.

TABLE X

ERROR RATES

Day/Mo/Time 1959	Operating Time in Hours	Error Rate Words in Error Per Minute	Error Rate Bits in Error Per 10^5 Transmitted	Average Nr. of Bits in Error in a Word in Error
2-3 Nov 2020-1220	16.1	0.0155	.079	3.067
3-4 Nov 1515-1330	22.7	0.0271	.077	1.706
4-5 Nov 2100-1330	16.5	0.0413	.119	1.722
5-6 Nov 1500-1330	22.4	0.1700	.035	1.217
6-7 Nov 1415-1330	23.5	0.0056	.011	1.125
7-8 Nov 1350-1330	23.6	0.0077	.039	3.000
8-9 Nov 1345-1330	23.8	0.7214	6.32	5.256
9-10 Nov 1640-1330	20.8	0.0040	.009	1.400
10-11 Nov 1545-1330	21.7	0.1000	.277	1.661
11-12 Nov 1400-1340	23.5	0.0857	.568	3.975
12-13 Nov 1400-1330	23.6	0.0423	.254	3.594
13-14 Nov 1340-1015	20.3	0.4638	.78	1.009
14 Nov 1100-1330	2.35	0.0070	.012	1.000
14-15 Nov 1415-1330	23.2	0.0007	0.001	1.000
15-16 Nov 1730-1330	20.1	0.0049	.008	1.000
16-17 Nov 1345-1330	23.5	0.0418	.078	1.123
17-18 Nov 1415-1330	23.2	0.0626	.243	1.814
18-19 Nov 1400-1400	23.2	4.0028	18.7	2.843
19-20 Nov 1600-1330	21.4	0.0848	.342	2.418
20-21 Nov 1940-1330	17.7	0.0066	.019	1.714
21-22 Nov 1736-1330	19.9	0.0008	0.001	1.000

TABLE X (Cont)

ERROR RATES

Day/Mo/Time 1959	Operating Time in Hours	Error Rate Words in Error Per Minute	Error Rate Bits in Error Per 10^5 Transmitted	Average Nr. of Bits in Error in a Word in Error
22-23 Nov 1410-1448	24.6	0.0040	.008	1.167
23-24 Nov 1502-1400	22.5	0.0740	.275	2.225
24-25 Nov 1417-1330	23.2	0.0439	.09	1.227
25-26 Nov 1445-1300	21.3	0.2349	.588	1.502
26-27 Nov 1345-1030	20.2	0.6570	1.58	1.447
28-29 Nov 1645-1500	21.7	0.0115	.045	2.333
29-30 Nov 1510-1700	19.3	0.0905	.272	1.800
30 Nov-1 Dec 1710-0945	16.3	0.0204	.043	1.263
4-5 Dec 1606-1330	21.1	0.0276	.116	2.519
Average		0.2549	0.882	3.17
Average without 8-9 Nov and 18-19 Nov		0.0848	0.164	1.819
Total Operating Time	623.3			

12. AN/FGC-29 and AN/FGC-54 Tests [14].

a. Data transmission tests were performed with an FSK system (AN/FGC-29) and a PSK system (AN/FGC-54) over a 5,000 mile H.F. ionospheric circuit from Hawaii to Fort Monmouth, New Jersey. Final results of these tests are discussed in detail in a report by General Dynamics. Generally the transmitter power output was maintained at 500 watts average; the power was decreased when no errors were produced and increased when errors in excess of 80 per minute were produced.

b. The test method was essentially the same for both equipments. Earlier tests had used a standard "Fox" message, but the tests under discussion placed primary emphasis on a pattern generator since it was desired to perform the tests on a fine-grain bit-by-bit basis instead of on a character basis and to apply the results primarily to digital data transmission. Alternate marks and spaces of equal length were applied to 12 channels of AN/FGC-29 and 36 channels of AN/FGC-54, with the waveshapes being shifted by a multiple of 60° in the various channels. Errors and distribution of errors were recorded at the receiver and inserted in a computer to compile error statistics. The operating frequency for the H.F. ionospheric circuit ranged from 11.0 to 23.6 mc.

c. The data rate per channel used for each of these equipments during these tests was 75 bits/second. Since the AN/FGC-29 has 16 channels, its total data rate would be 1,200 bits/second. Since the AN/FGC-54 has 40 channels, its total data rate would be 3,000 bits/second. Median bit error rates for AN/FGC-29 ranged from 2.7×10^{-3} to 2.4×10^{-6} and rates for AN/FGC-54 ranged from 7.6×10^{-3} to 5.2×10^{-5}.

d. The median bit error rate (BER) as a function of signal-to-noise ratio (both with and without observed selective fading) is shown in Figure 7 for AN/FGC-29 and in Figure 8 for AN/FGC-54.

e. For AN/FGC-29 and AN/FGC-54, tested as indicated above and considering only one-minute sample error totals not greater than 20, the two systems are not significantly different with respect to producing clusters of consecutive errors. Generally, over all propagation conditions for BER of 5.2×10^{-3} or less, single errors account for 81% of all accumulated errors in each system, double errors were 13%, triple errors were 5%, and quadruple errors were 1% for each system. For these BER's, quintuple errors were almost non-existent and no error cluster greater than five was observed.

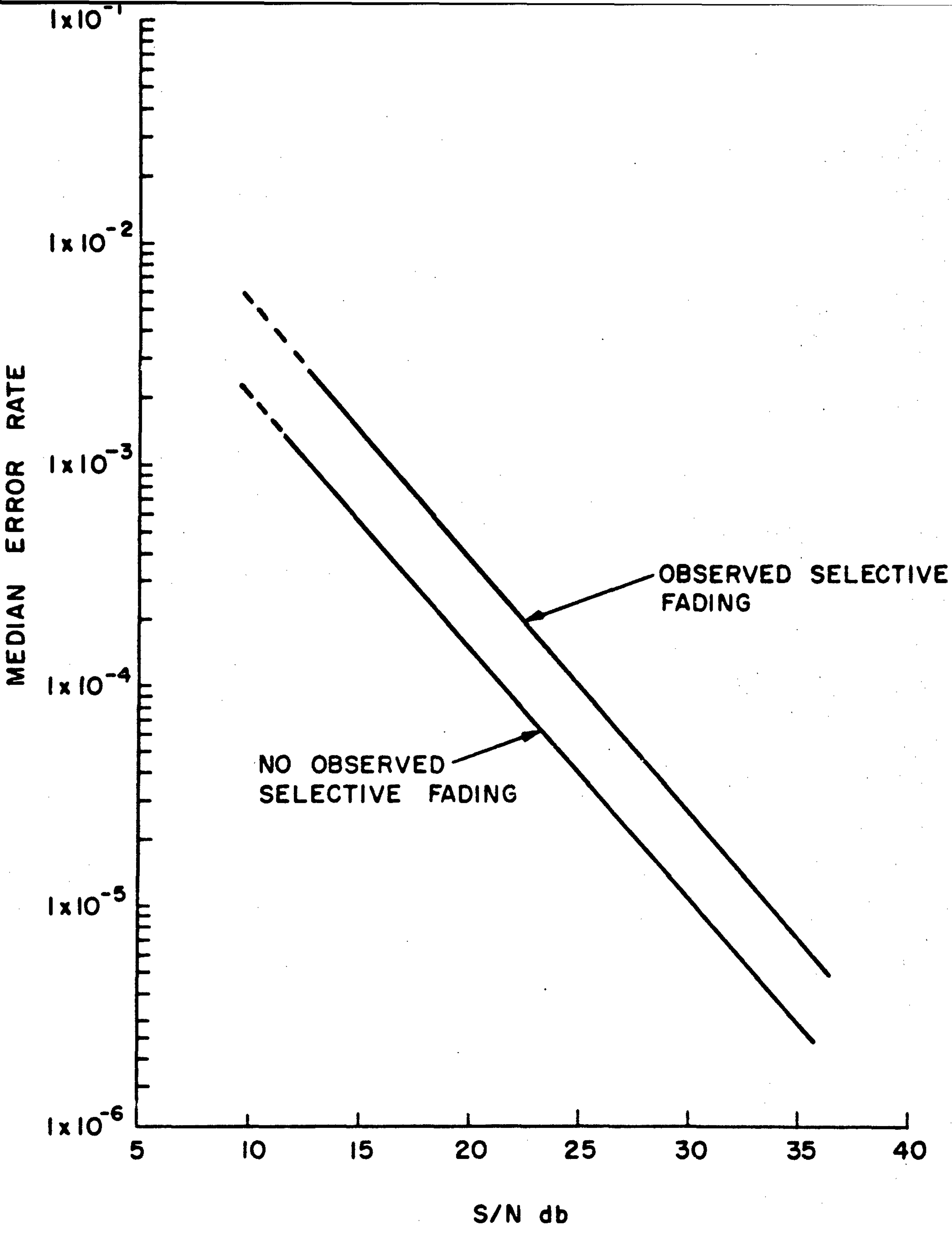


FIG. 7 AN/FGC-29 GROUPS II AND III COMBINED

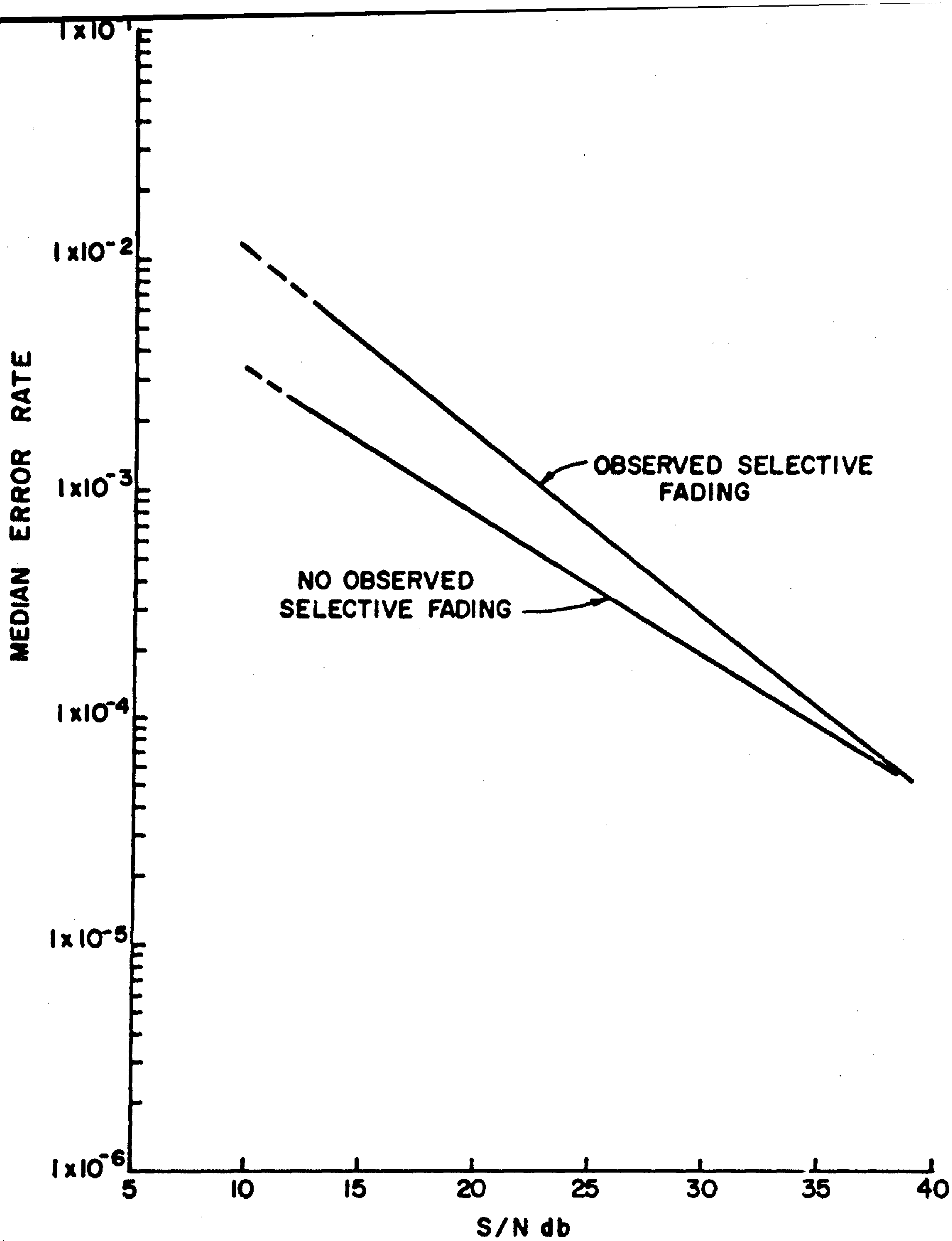


FIG. 8 AN/FGC-54 GROUPS II AND III COMBINED

13. UNICOM H. F. Transmission Test Program [15].

a. A series of digital data transmission tests are being conducted to determine the suitability of various transmission media for the transmission of UNICOM formated data. An instrumentation package has been developed to perform the data gathering. Testing has either been performed or is scheduled on H. F. radio circuits, a tropospheric scatter circuit and a number of wire line circuits. The test program has its primary aim in demonstrating the transmission of UNICOM formated digital data; however the results of the tests are in a sufficiently flexible form to permit their use in predicting general digital transmission performance characteristics. Partial results of tests in all transmission areas are available and some are given below. Examples of the data reduction process will be given for those areas where such examples have already been obtained.

b. The test instrumentation will provide a permanent recording of the detailed bit-by-bit (fine grain) results, in a format from which any required statistics can be obtained using an electronic computer. On facilities with rates in excess of 42 kb/s, the package can be simply modified to provide error data on a sampling basis. This allows for considerable flexibility over an arrangement whereby fixed data reduction is done at the test site in real time. In operation, the instrumentation records only error states of received data bits, using a start-stop and buffer technique, thus saving on tape usage by not recording error-free data intervals. Time reference for bits in error is supplied so the error data is recorded in characters. These characters are arranged in blocks called "words" along the tape length and words are further arranged to make up "records".

c. The instrumentation contains a feature whereby it is possible to record errors in an alternate mode (Mode II) when the error rate over the transmission facility becomes so high than bit-by-bit statistics are no longer important, and excessive tape would be used by recording in the Mode I (bit-by-bit). Mode II is automatically applied whenever the error rate being recorded continuously exceeds a preset, but variable threshold for a period of three minutes. During the three minute interval, fine grain data (Mode I) is still recorded but after the three minute period the instrumentation will record in the Mode II until the error rate falls below the present threshold, whereupon the recording reverts back to the Mode I. In Mode II, the instrumentation records the number of error bits in every block of 17 bits but does not provide "position within the block" data as does the primary mode.

d. The instrumentation package is used in conjunction with synchronized pseudo-random word generators to obtain transmission error data over the transmission facilities.

e. A major part of the UNICOM data transmission tests program over H. F. radio concerns the detailed Mode I recording of H. F. error information on magnetic tape for computer processing. The particular terminal equipment arrangement provides for the conversion of a pseudo-random bit stream at 2,550 bits per second into 32 parallel frequency division multiplexed FSK channels for transmission over an H. F. test circuit. A basic arrangement was used consisting of a serial to parallel converter followed by two AN/FGC-29's in parallel. Each AN/FGC-29 provides 16 FSK parallel channels. Two AN/FGC-29 equipments used simultaneously provide the required 32 channels needed when a 2,550 bit/second serial pseudo-random test stream is converted into a 32 parallel channels. Therefore, each of the 32 FSK channels is keyed at approximately 80 bit/second. Each group of 16 channels occupies a frequency interval of 3 kc and the two slots used (6 kc) are positioned within the usual 12 kc bandwidth of a single side band transmitter. The remaining 6 kc contains normal teletype traffic and order wire facilities. Receiving is accomplished on a space diversity basis, combining being accomplished per channel, in the AN/FGC-29's. An H. F. test path from Frederick, Maryland to Pirmasens, Germany utilizing STARCOM facilities was set up and used for about one year. This path, about 4,000 statute miles long, was investigated first by cumulative error counts punched out on paper tape (course grain) and later by the tape instrumentation described above. In both cases, a pseudo-random data pattern was used with an identical pattern generator and comparator circuits at the receive end. In all, about 129 hours of data was obtained. This path was replaced with one from Frederick, Maryland to Leavenworth, Kansas as a result of continually poor data performance characteristics of the overseas circuit. This second circuit is approximately 1,000 miles in length. In this arrangement, it is intended to perform extensive full duplex digital data tests, in addition to a variety of subjective evaluation tests. Testing over this circuit (unidirectional) with the fine grain instrumentation described above has already resulted in some 62 hours of magnetic tape records.

f. The results of coarse grain data accumulated over the two H. F. paths described above are presented graphically in Figure 9 to Figure 12. These recordings were made prior to the use of the fine grain instrumentation described above and give only cumulative error statistics. Pseudo-random test patterns were used in all cases. Two types of representation are shown, daily cumulative error rate vs day of test, and error rate vs time of day which shows 15 minute averages plotted against an hourly scale.

g. The fine grain error statistics presented in Figures 13 and 14 are the initial results from preliminary computer reduction of the fine grain measurements taken with the instrumentation described above. The reduction was accomplished on a 7090 computer. These curves show the cumulative distribution of error free intervals vs the length, in bits, of the interval. Curves are drawn for both H. F. paths under test. The two dotted curves on each graph represents test data taken on both path in Mode I (low error mode) and the 3 minute intervals of high

error rate during which fine grain recordings are still made (high error mode). The solid curves are theoretical, and represent the distributions which would result if the error statistics were assumed to be truly random in nature. The ordinates of the graphs are interpreted as the probability that the length of the error free interval does not exceed the value of the absissca, k. The curves show that the Leavenworth circuit yielded a higher percentage of longer error free intervals than did the longer Pirmasens circuit. It also shows that for low values of k, the results approximate that of a truly random media, but for higher values of k, saturation occurs sooner than for the assumed case. This indicates a situation where a departure from a strictly random situation appears to be occurring which limits the distribution of actual error free intervals for larger k.

h. Among the statistics which will be derived from the data are the following:

(1) Channel Bit Error Rate. This describes the error rates of the individual AN/FGC-29 FSK channels used in the test, and is useful in determining which channels contribute most to the overall error rate.

(2) Multiple Bit Errors. This statistic yields information concerning the distribution of error bursts in the data. For practical purposes an error burst is defined as one in which no more than three consecutive error free bits appear. In other words, error bursts are separated by error free intervals which are four bits or longer.

(3) Error Free Intervals. The distribution of error free intervals will be computed as an aid in specifying optimum block lengths for store and forward techniques.

(4) Correlation Between Bit Errors. This computation involves the conditional probability that given an error, another error will appear, a fixed number of bits (k) later. This computation is made for a wide range of values of k, and is important in determining the time separation of signalling and framing bits for optimum results.

(5) Bit Combination Errors. Correlations are made between sequences of error bits and the transmitted test pattern, on the basis that certain combinations of transmitted bits in combination with the memory of the channel may produce intersymbol interference.

(6) High Error Rate Distributions. Often in H. F., periods of high error rate are experienced (greater than 1 in a hundred). Information regarding the distribution of errors during these periods, is useful in deciding the usefulness of vocoded speech over H. F. at these high rates. The alternate mode (Mode II) described above is useful in providing this information.

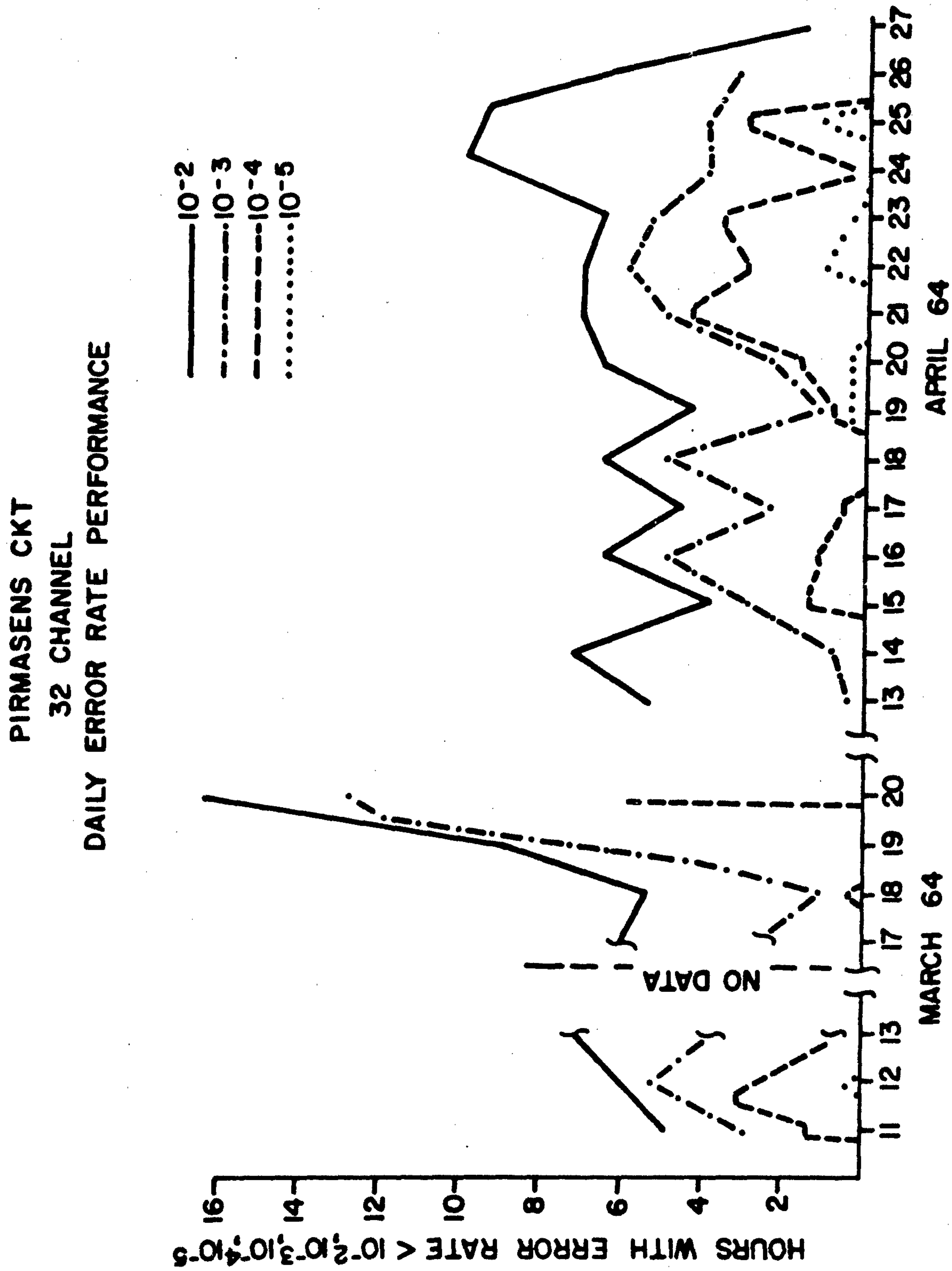


FIG 9 COARSE GRAIN DATA

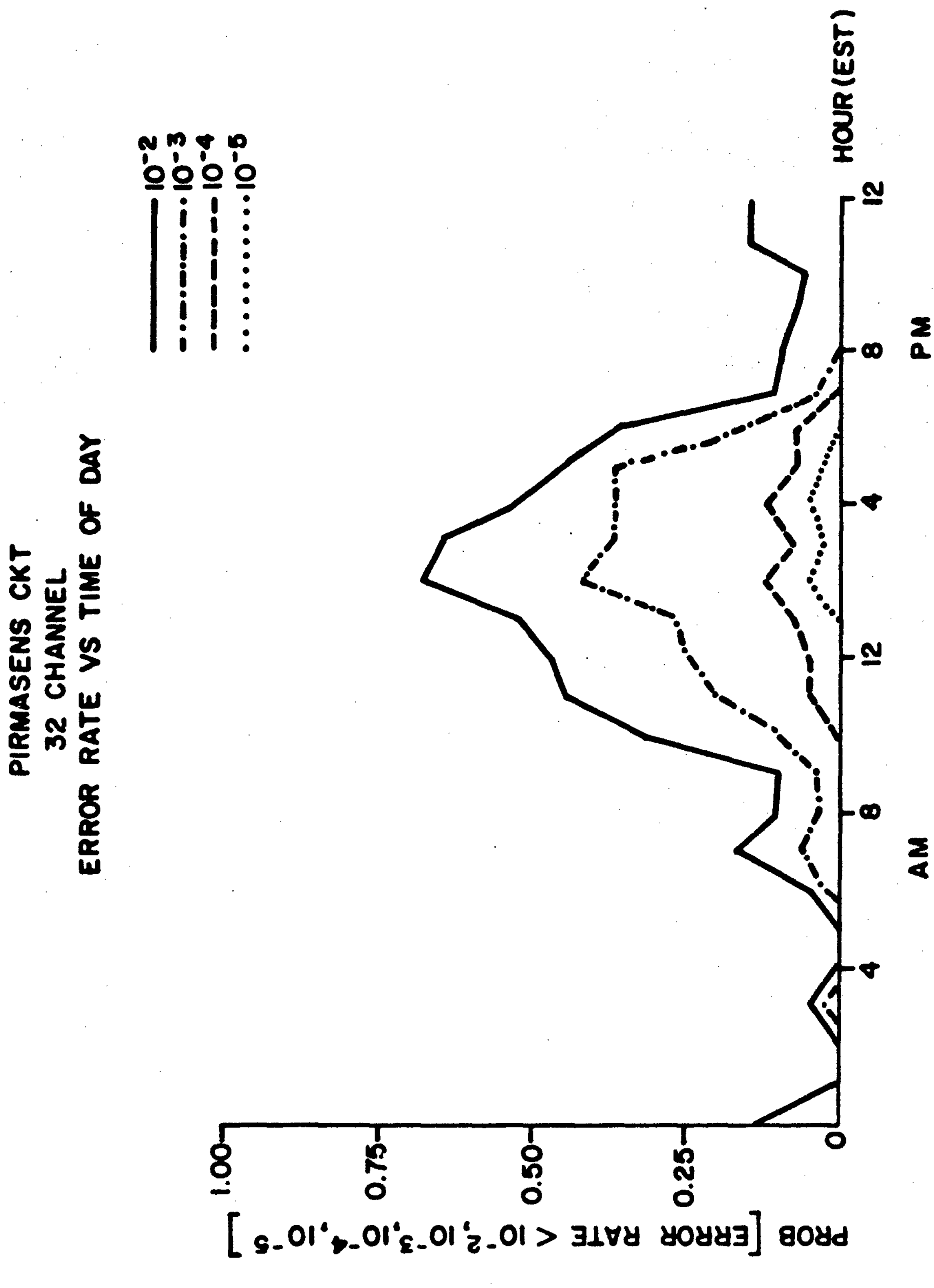


FIG. 10 COARSE GRAIN DATA

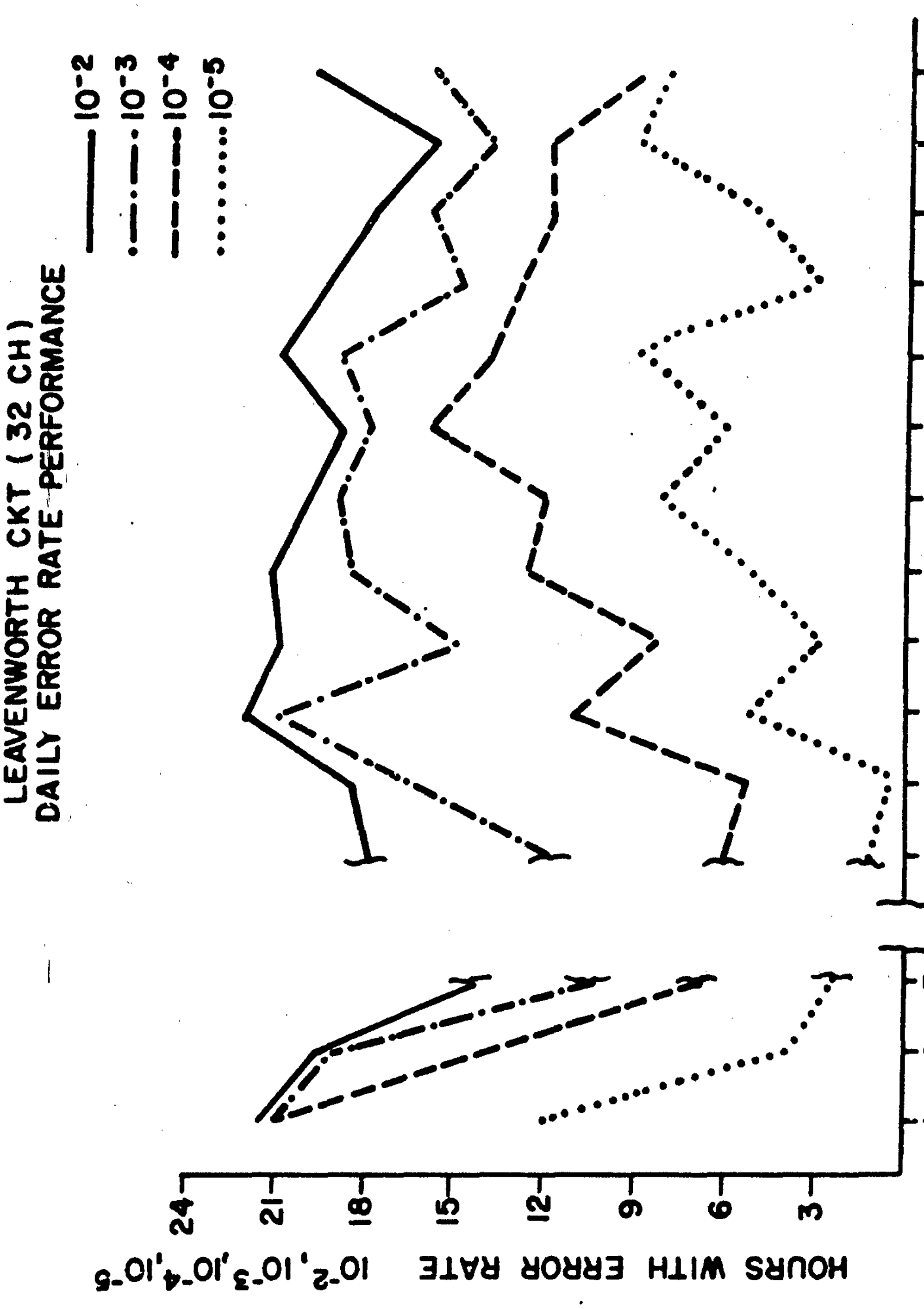


FIG. 11 COARSE GRAIN DATA

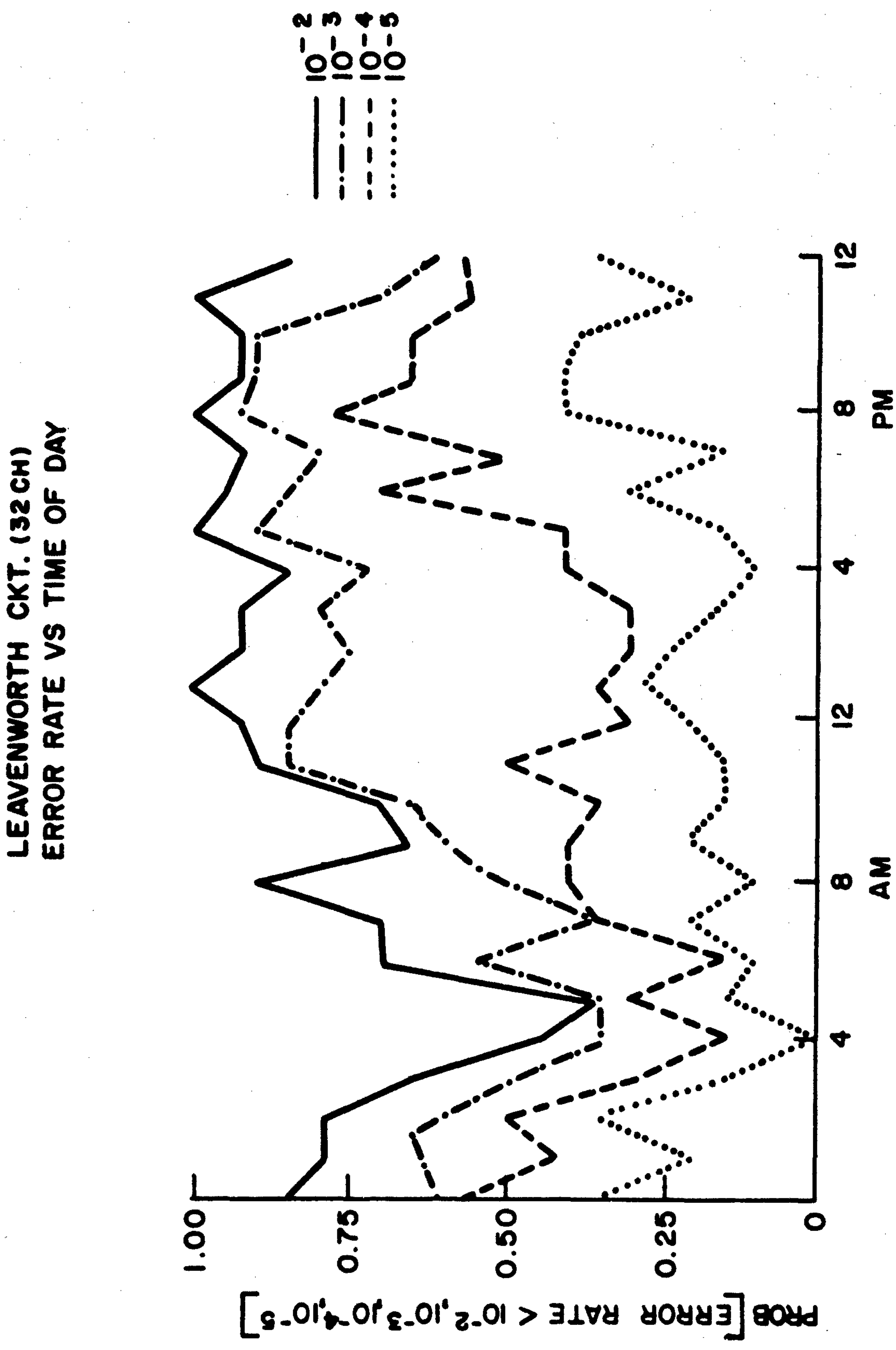


FIG. 12 COARSE GRAIN DATA

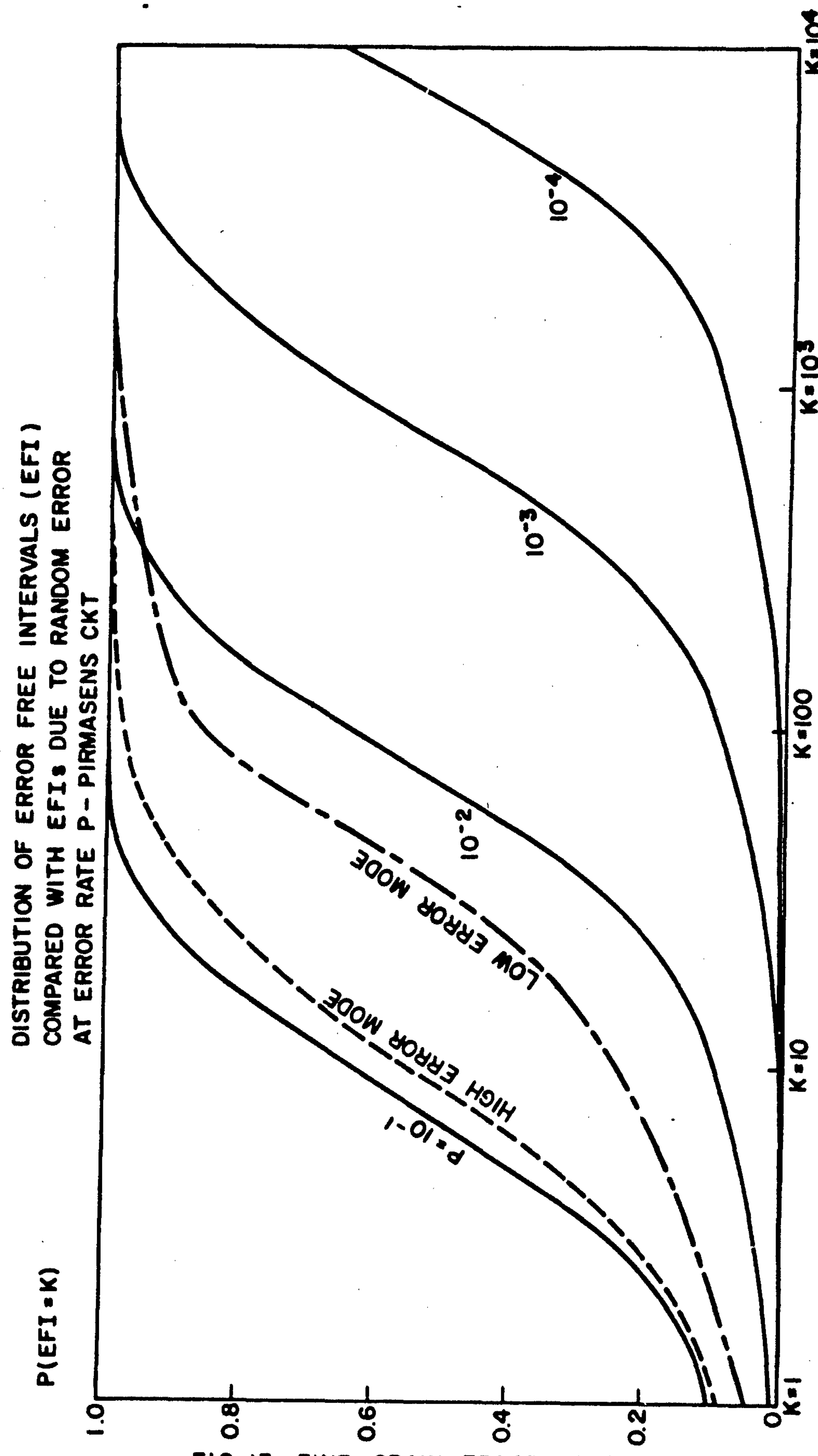


FIG. 13 FINE GRAIN ERROR STATISTICS

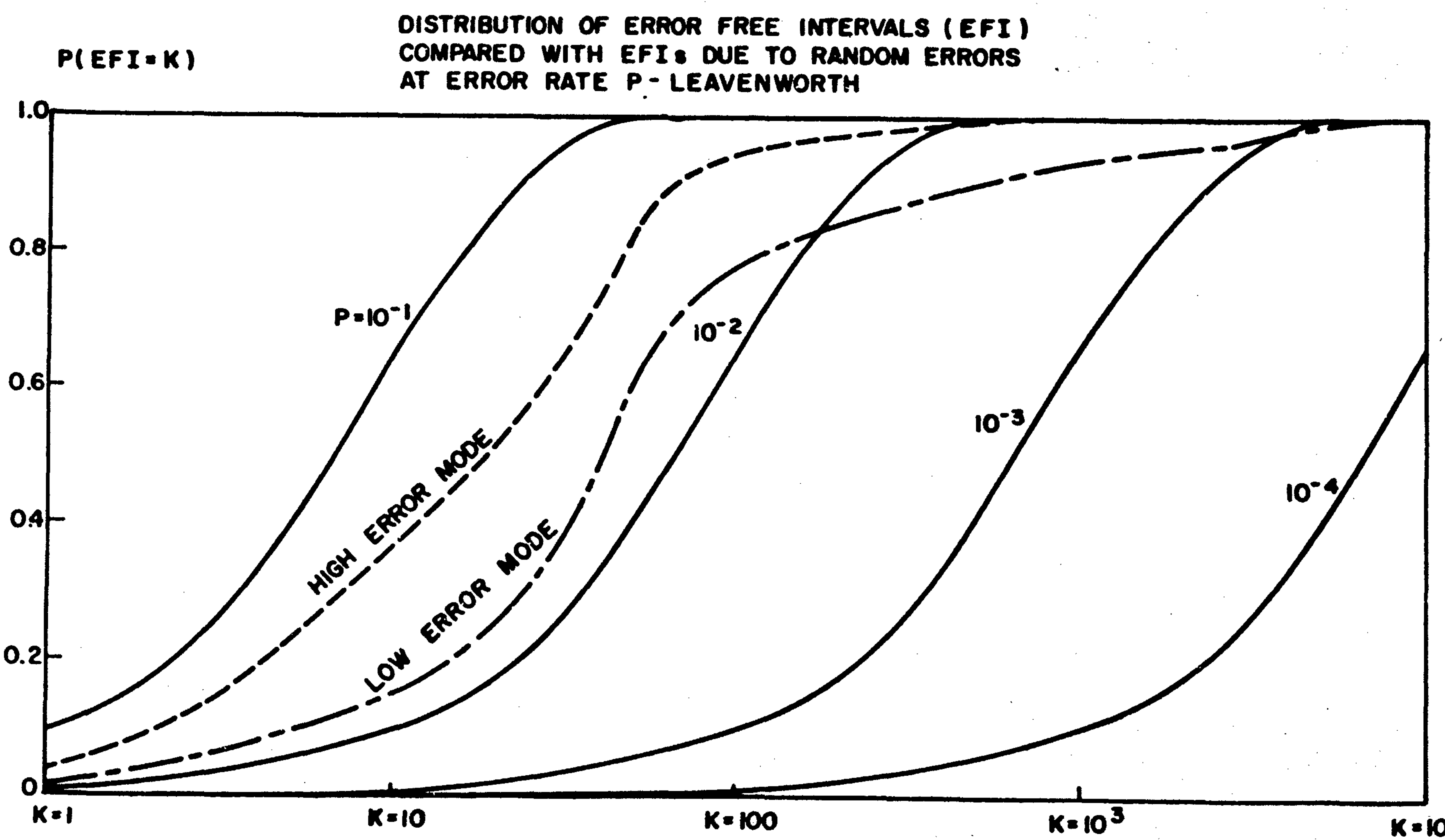


FIG. 14 FINE GRAIN ERROR STATISTICS

14. Ionospheric Scatter Tests.

a. An ionospheric scatter teletype circuit (32.5-37 Mc) between the United Kingdom and Iceland (about 1,144 miles) was tested by the SHAPE Air Defense Technical Center [16, 17] to determine the effectiveness of ARQ (automatic request) telegraph equipment. The ARQ equipment encodes each standard 5-unit character to a 7-unit code in such a manner that each character has an identical (3:4) mark/space ratio. Changes in this ratio at the receiver are used to detect mis-selected characters and the ARQ equipment requests that they be repeated. Hence this equipment reduces errors on teletype circuits at the cost of a reduced average information rate. The ARQ equipment, type TOR E1, used for these tests utilizes an essentially synchronous system and provides for 4-channel duplex operation by means of time division multiplex.

b. In general, on H. F. circuits, the received signal falls from a workable to an unusable value in a relatively short time, after which a change of frequency is necessary to maintain communication. On ionoscatter circuits, there is almost invariably a background signal present. ARQ systems are potentially capable of operating throughout the low signal periods.

c. The channel data rate selected for the tests was 42 6/7 bits per second. The test results are in terms of character errors in a system using error detection and retransmission of data (ARQ system). Estimates of binary error rates (bit error rates) have been deduced for an unprotected system (not using ARQ error-reduction) and these estimates can be compared with other bit error rates.

d. Estimates of binary error rates which would have occurred if ARQ error reduction techniques had not been used range from 2×10^{-3} for a S/N ratio of 15.4 db (received median S/N ratio in a 3 kc band) to 4×10^{-5} for a S/N ratio of 25.3 db.

e. Slowdown and error rate is shown in Figure 15. Curve A shows the speed reduction (reduction in data rate) due to retransmission of data in the ARQ process. Curve A (solid line) is a smoothed weighted curve from measurements for about half a year. The dotted lines on each side of curve A are the limits of smoothed curves plotted on a monthly basis. These curves show reductions in data rate from 60% for a S/N ratio of 0 db to less than .001 of 1% for a S/N ratio of 30 db. Curve A is based on half-hour medians, and one repetition only during a half-hourly period represents a slowdown of about .0365%, so the accuracy of the curve below this figure is not certain. Curve B shows the character error rate, with the limits shown on each side in dotted lines. These curves show a range of character error rates ranging from 2.7×10^{-2} for a S/N ratio of 0 db to less than 10^{-5} above 12.5 db. The number of half-hourly periods during which no errors were printed and the number of periods of no repetitions or slowdown of data rate are indicated in a box graph at the bottom of the figure. It will be noted that the error-free periods of 1/2 hour or longer occur mostly between 10 and 30 db.

ARQ TEST ICELAND - UK

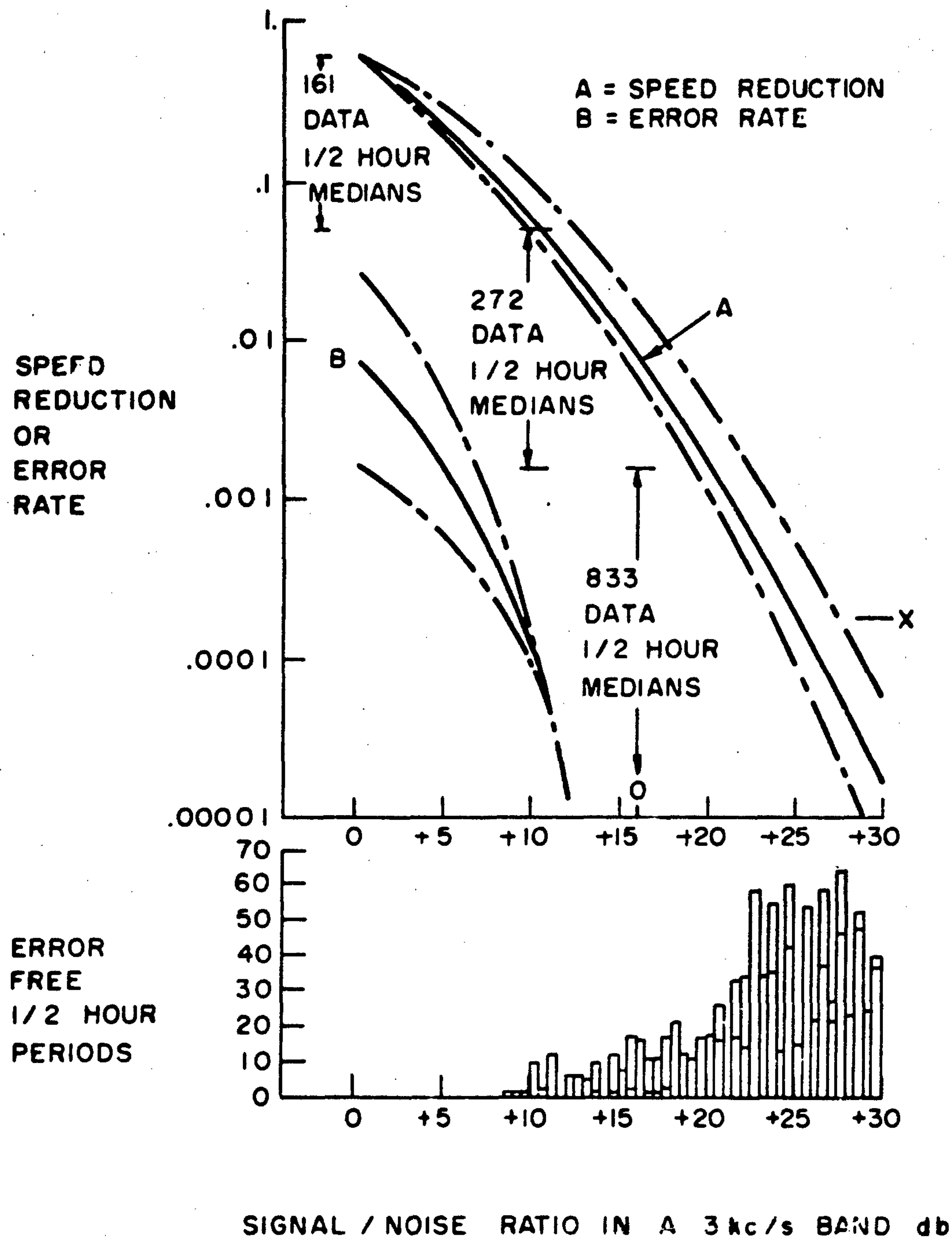


FIG. 15

15. Various Telephone Circuit Test Results.

a. The results of several tests have been reported by Rand and published by Lincoln Laboratory [10, 18, 19]. These tests include:

Test A. Kingston-Canaveral tests (1960)

Test B. Kingston-Canaveral tests (1958)-Circuit A

Test C. Kingston-Canaveral tests (1958)-Circuit B

Test D. Lexington-South Truro test (1959)-Circuit A

Test E. Lexington-South Truro test (1959)-Circuit B

Test G. "Hawaiian" Cable tests (1960)

b. Test G has been discussed previously. Tests A, B and C were on long-haul telephone facilities (1,500 miles). Tests D and E were over comparatively short-haul telephone facilities (125 miles). For these tests, the percentage indicated is of the total test time and not of the whole year. Tests F, H and J refer to estimates of L. F. radio bit error rates. The results are shown in Figure 16.

c. Additional comparative data on the Hawaiian cable and other telephone facilities referenced above are available in a paper by Hofmann.[39]

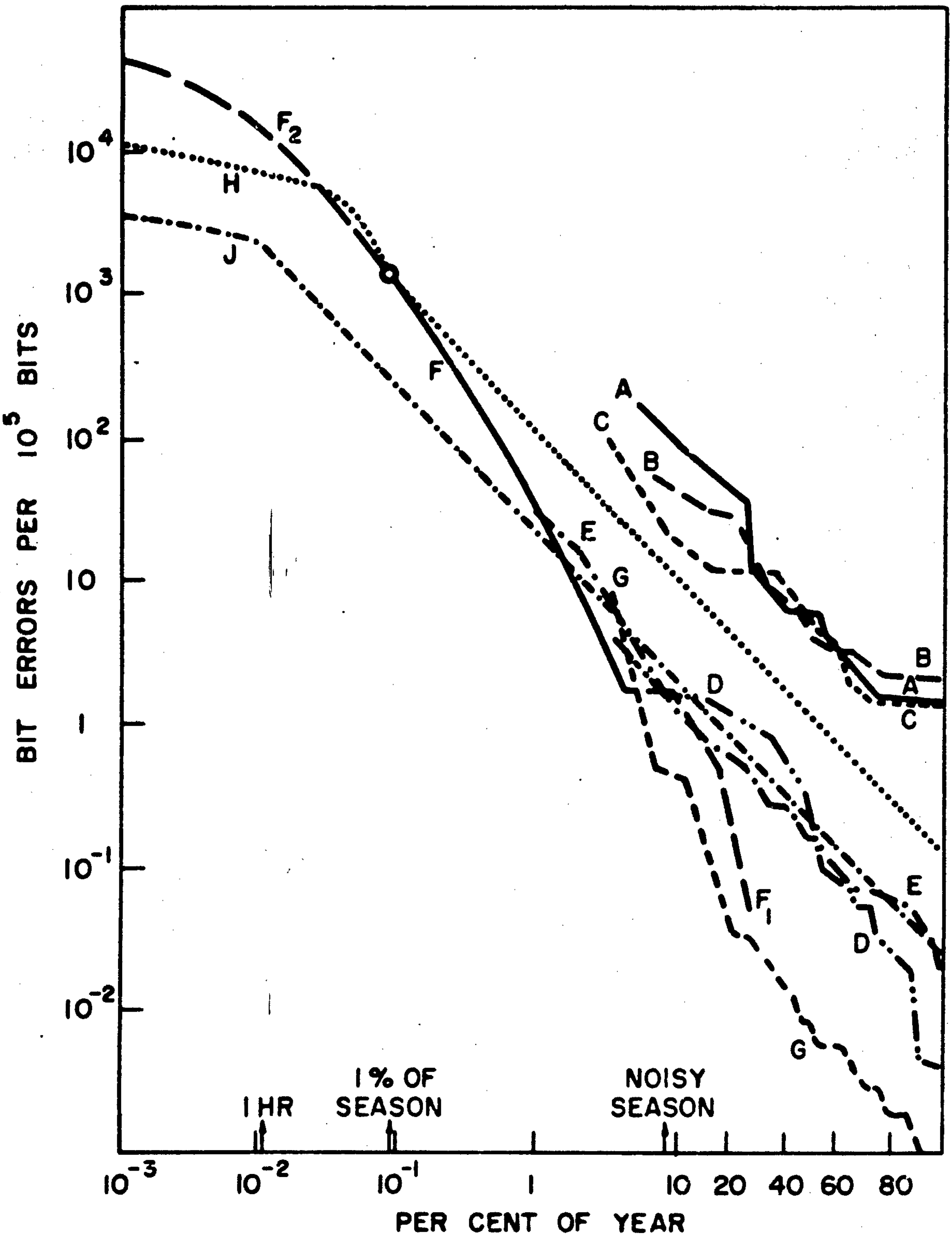


FIG. 16

EXPERIMENTAL RESULTS– MEASURED PERFORMANCE CHARACTERISTICS OF VARIOUS COMMUNICATIONS CIRCUITS – COMPARISON WITH ESTIMATES FROM ATMOSPHERIC NOISE FOR LF RADIO LINK

16. TD-2 Radio Circuit Tests.

a. Data transmission tests [20] were made by Bell Telephone Laboratories on looped circuits from Whippany. New Jersey which included multi-link TD-2 radio and submarine cable. The transmission paths included 98 miles of cable pairs to New York City. 6,116 miles of TD-2 radio to Oakland, or 6,364 miles to Point Arena. California. and 5,200 miles of submarine cable to Hanauma Bay, Hawaii. Total testing time was 271 hours on TD-2 and 111 hours on TD-2 and the Hawaiian cable. FSK modulation at 1500 $\pm$ 375 cycles in the California tests and 1700 $\pm$ 375 cycles in the Hawaii tests was employed.

b. Data was transmitted at 750 and 1500 bits/second. The combined bit error rate for all tests was 2×10^{-3}. The loop including TD-2 and the "Hawaiian" cable produced a bit error rate of 1.335×10^{-3}, of which 99.8 of the total bit errors could be attributed to TD-2. Hence the cable produced an error rate of 2.67×10^{-6} and the TD-2 an error rate of 1.332×10^{-3}.

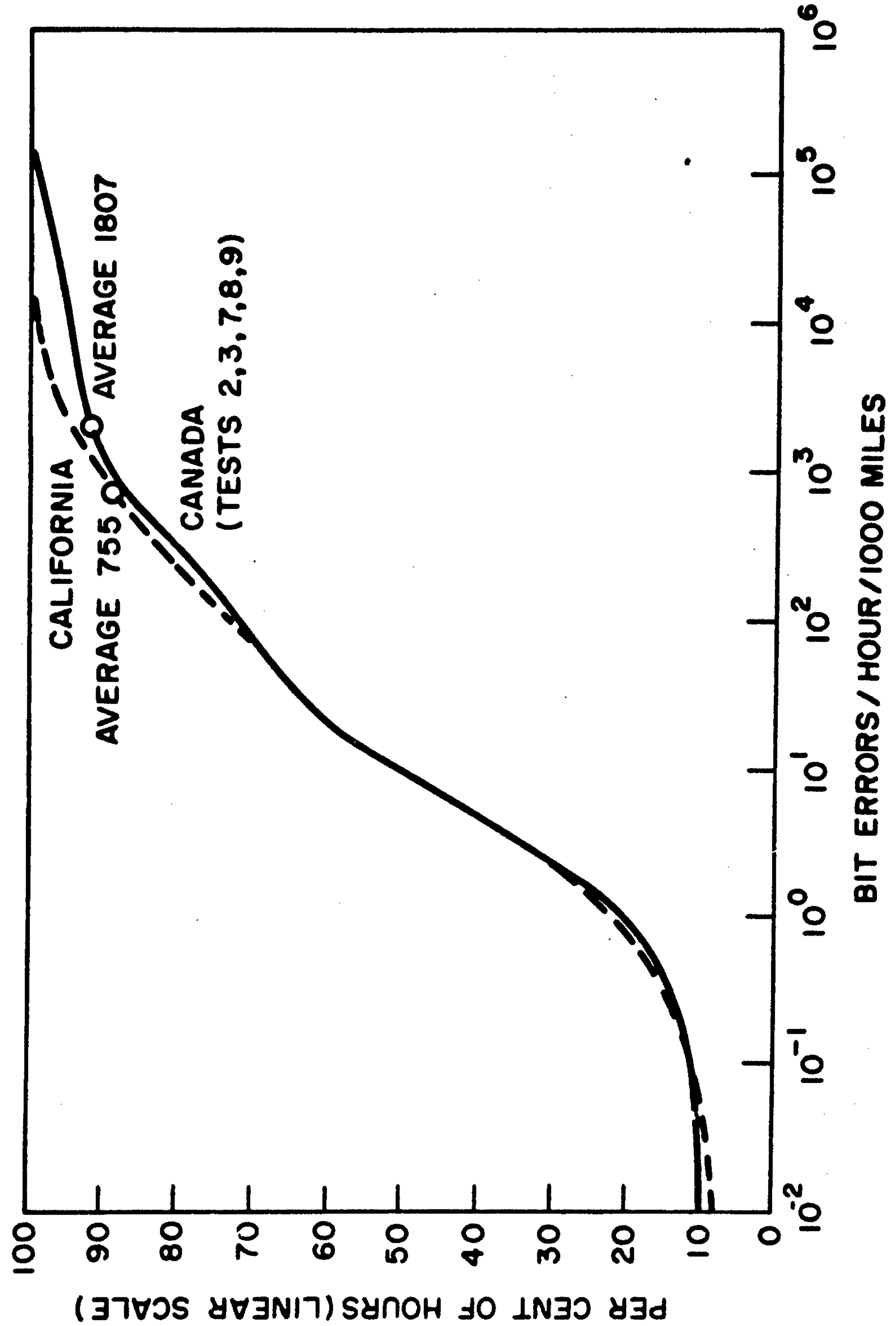
c. The UNICOM report [20] indicates that "Test results on the TD-2 system showed relatively long periods (median interval around 30 minutes) of error-free transmission interrupted by hits of variable duration. The hits of long duration, although relatively few. were responsible for the high overall error rates. For example. 2 percent of the hits produced 80 percent of the bit errors." Deducting the bit errors due to the longer hits, which were assumed to be circuit interruptions, resulted in an error rate of between 2 and 3×10^{-4}.

17. TD-2 and Troposcatter (U. S. - Canada Tests)

a. A series of data transmission tests [20] was made on looped circuits from Whippany, New Jersey to various points in Canada through multi-link TD-2 radio and tropospheric scatter systems. The individual loops or combinations of loops tested included various portions of UHF radio, 2,767 miles of TD-2 radio and 2,067 miles of troposcatter links. Results of the tests were almost the same as in the California tests discussed in paragraph 16 during 90% of the time and were up to 10 times worse in error rate during the remaining 10% of the time due to more severe circuit interruptions.

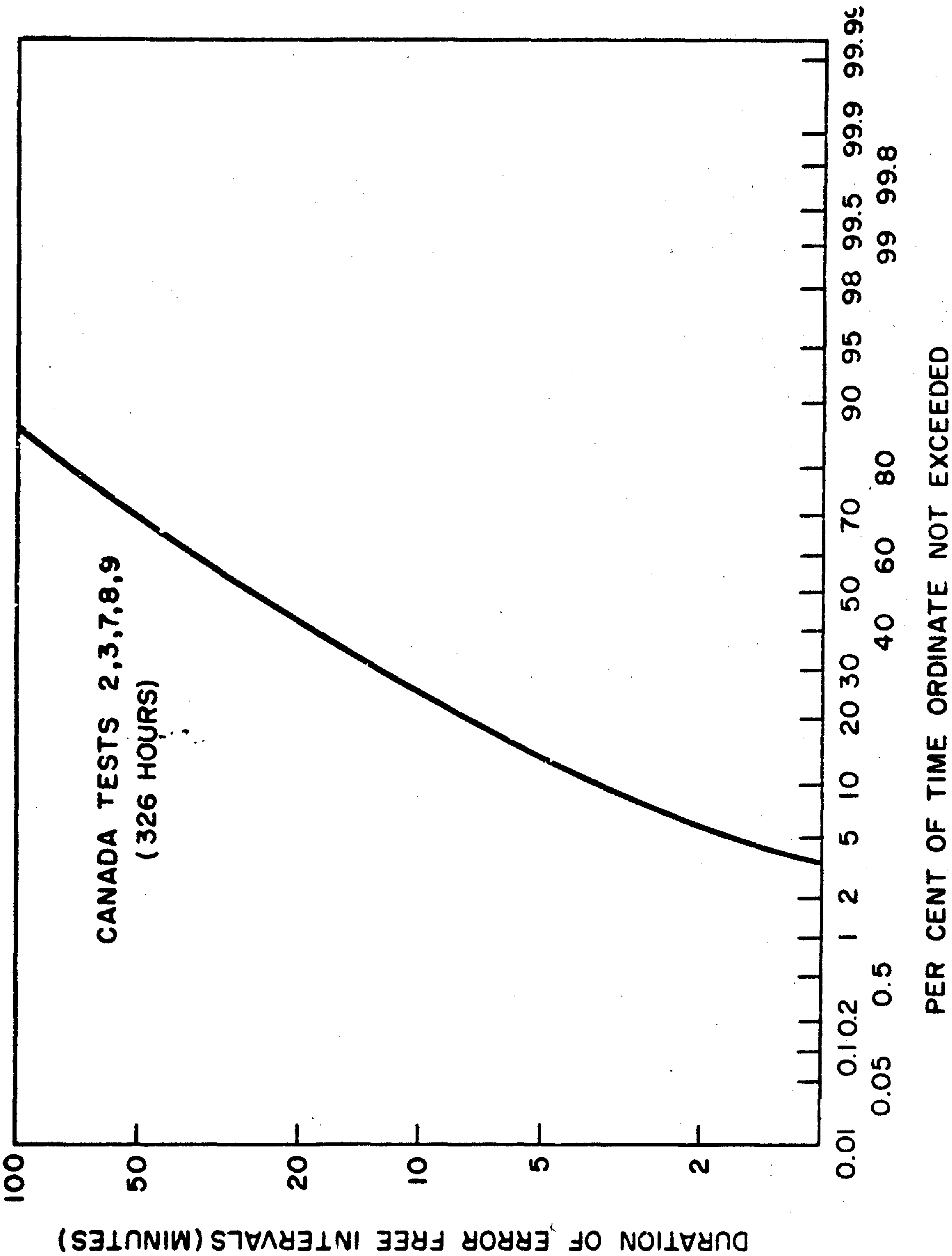
b. "FM750" data (FSK modulation at 750 bits/second) was transmitted from Whippany. Figure 17 compares the overall results of the California and the Canada tests on the basis of time distributions of hourly bit error rates per 1,000 miles and shows the deviation in error rates past the 90% point. The average error rate per 1,000 miles is 3×10^{-4} for the California tests and 7×10^{-4} for the Canada tests. These values may seem quite large, but if they are restated as a bit error rate per mile the error rates are 3×10^{-7} and 7×10^{-7} respectively.

c. According to the UNICOM report [20], "The division of errors between the TD-2 and troposcatter circuits seems to correspond to their respective circuit lengths. -- An analysis of the error results indicates that data transmission performance for combinations of multi-link TD-2 and troposcatter systems is similar to that for the TD-2 systems only. The natural deduction that troposcatter and TD-2 performances are similar seems to be verified by finding average error rates separately. The average number of bit errors per hour per 1,000 miles was 1,810 for either the TD-2 or troposcatter case. Results further showed, just as in the case of the California loops, that approximately 1% of the total number of hits produced around 99% of the total number of bit errors." Deducting the bit errors due to the longer hits which were assumed to be circuit interruptions resulted in an error rate between 1 and 4×10^{-4}. "In both sets of tests, the intervals between errors were 27 minutes or longer for 50 percent of the time." The curve for error-free intervals for the Canada tests is shown in Figure 18.



HOURLY BIT ERROR RATES PER 1000 MILES
ON LOOPS TO CANADA AND CALIFORNIA

FIG. 17



DURATION OF ERROR FREE INTERVALS VS PER CENT
TRANSMISSION TIME

FIG. 18

18. "White Alice" Tests (Alaska).

a. The White Alice system[20,21] is an extensive communication network comprising 3,000 miles of multiplexed radio. telephone and telegraph circuits covering the State of Alaska. Much of the mileage consists of tropospheric radio links making White Alice the largest system with this type of transmission. The system is made up of 23 tropospheric links operating in the 750-950 mc band and 9 line-of-sight microwave links. Much of the information and curves describing the White Alice system is a composite of tropospheric scatter and line-of-sight transmission, but some of the information pertains specifically to the tropospheric scatter radio link from Lisburne to Kotzebue, a distance of 170 miles. The radio transmitter power was 10 kw. The data signals made use of on-off double side band amplitude modulation with a 1500 cycle carrier. The data channel was one of several telephone channels transmitted through the radio link.

b. The data rate was 750 bits/second, and the error rates varied from 10^{-2} to 10^{-6} (or 1% to 0.0001%) as shown in Figure 19. Measurements for this link were obtained during the winter of 1957 which was the worst month for radio transmission of the entire year. This link also gave the poorest results of any link in the entire system; thus, this can be considered as a "worst-case" test.

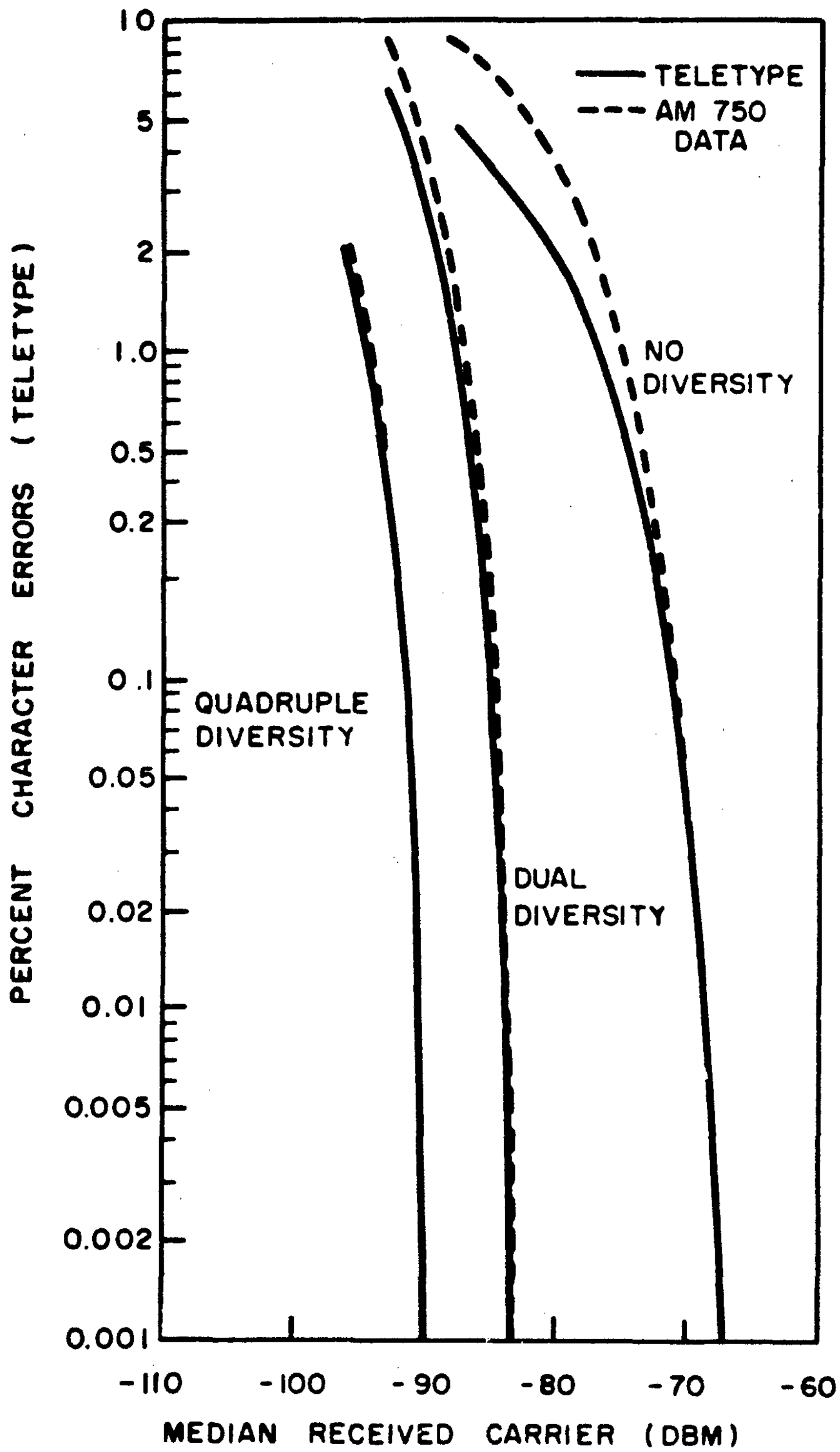


FIG. 19

TROPOSPHERIC SCATTER PERFORMANCE

19. Data Transmission Performance on Long-Haul Telephone Systems.

a. The evaluation performed by Dimock [22] is typical of dialled-up connections through the commercial network. Over 5 million mile-hours on ATT Co. line were involved. A bit rate of 750 bits per second was chosen so that the normal loss and delay characteristics would have little effect on the performance. Also, the use of looped-back circuits eliminated the need for recovering the timing from the received data signal. Only those error contributions due to circuit disturbances were, therefore, measured.

b. Long error-free periods - sometimes as long as several hours - were interspersed with periods of disturbances or interruptions of variable duration, ranging from milliseconds to several minutes. The longer disturbances - in the order of a second or more - were characterized by catastrophic degradations such as abnormally high noise or complete loss of signal power during which the error rate reached the maximum of 0.5, indicating no relation between the received and transmitted bits. Interruptions could not be divided up into long and short disruptions; a continuous distribution of duration of disturbances was found. The statistical nature of the disturbances cited makes it almost meaningless to state the performance of a data circuit solely in terms of a long-term error rate.

c. The modem used an FSK technique with a power of -14 dbm at the transmitting toll test board. Even at this low input level, errors were generally caused by catastrophic circuit degradations - not by white noise. The average noise power received on the circuits tested was from 25 to 35 db below the signal power.

20. Telephone Network Characteristics and Data Transmission Tests.

a. In his paper, Nast [23] shows that signal-to-noise ratio (in terms of white noise) is no great factor for the telephone network. Only 1% of the calls exceeded noise values of 40 dba at the receiver (equivalent to -42 dbm of white noise in a 3 kc band). With a signal input of -6 dbm at the transmitter and losses not exceeding 26 db, then the signal is at least 10 db greater than the noise, i.e., -32 - (-42) = 10 = S/N.

b. The conference papers by Alexander [24], Gryb [25] and Nast [23] do not mention circuit interruptions, dropouts, or fades. This might account for the statement that the correlation of impulses with errors was poor. In his field tests. Nast states that 40% of the calls through the telephone network failed to show any impulse counts regardless of the measured level. A plot, see Figure 20, is given of impulse strength versus impulse noise counts for 15 minute periods.

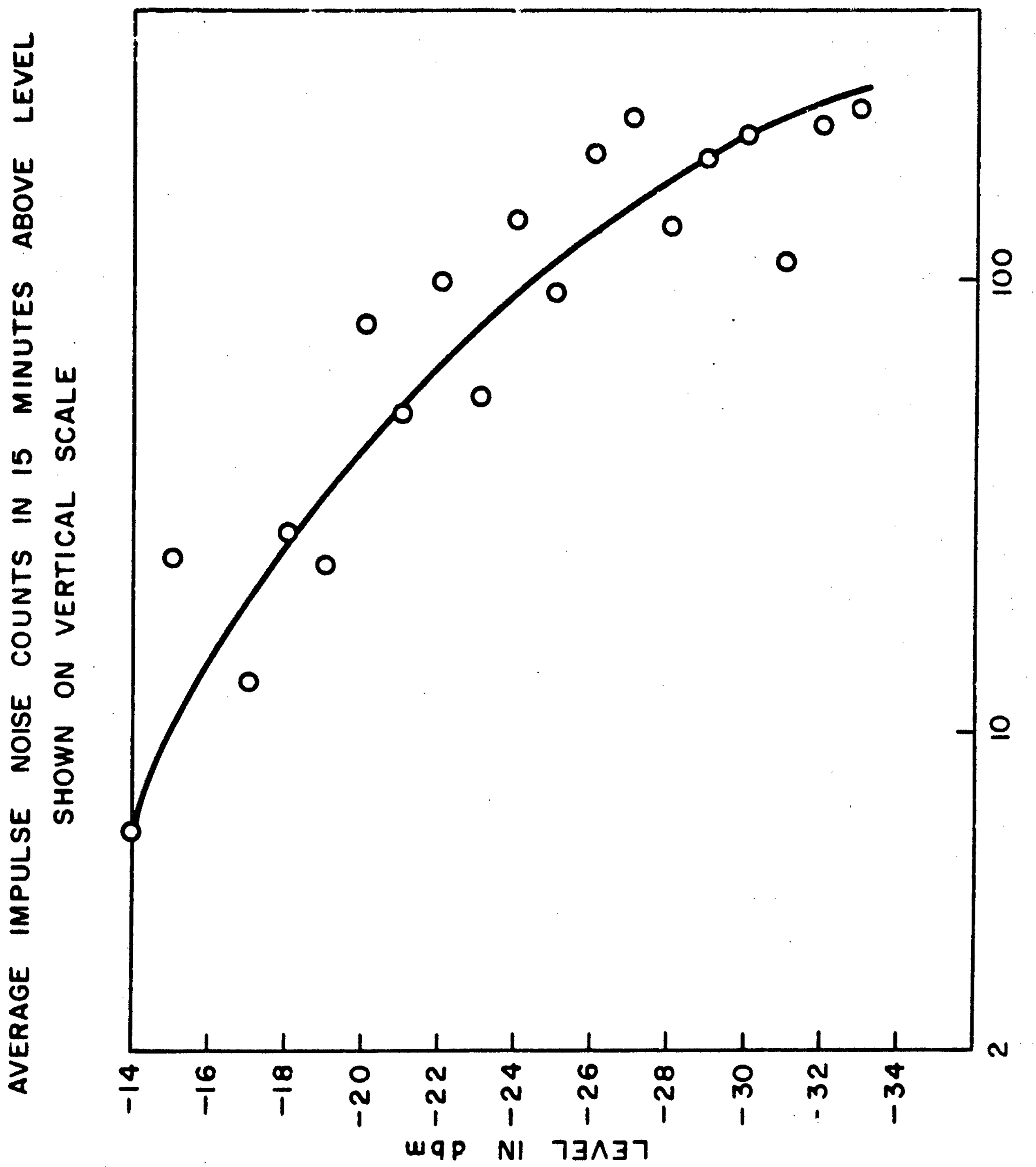


FIG. 20
AVERAGE IMPULSE NOISE COUNTS IN 15 MINUTES

c. The results obtained by the Data Transmission Evaluation Task Force of the Bell System and reported by Alexander, Gryb and Nast, were intensively investigated by Morris [26]. Although the data reported was biased against dropouts in the sense that faulty runs were discarded, Morris estimates that 20% of the reported errors were due to dropouts.

d. Although Alexander, Gryb and Nast did not monitor the line for dropouts, Morris was able to identify dropouts of fairly long duration by the distinctiveness of the resulting error pattern. It is pointed out that codes containing forbidden combinations, for instance a 2 out of 8 code, can be constructed to combat the effects of dropouts. This resistance to the effects of dropouts is due to the imbalance between the occurrence of marks and spaces, rather than to the processing of the redundant information (which may also be done).

e. With the modulation (i.e., 2 - state FM) and a zero-crossing detector, the appearance of signal fades or dropouts will cause the lower frequency state to be favored, while the appearance of impulse noise (provided it has higher-frequency components than the signal) will cause the higher frequency state to be favored. Here, again, if the statistics of the circuit perturbations are known, a code can be devised to lower the apparent bit error rate.

f. Morris notes that basically three types of errors occurred:

(1) Fades or signal dropouts - these favored space-to-mark errors.

(2) Impulse noise bursts - these favored mark-to-space errors.

(3) Bursts of errors coinciding with audible multifrequency key pulses. The received bit patterns seemed to follow the multiple of 200 cps which separate the two tones of an MF pulse. Traces of residual errors occurring at intervals of 57 bits, 320 bits, and 32 bits were found. He ascribed single bit errors spaced 57 bits apart (at 1200 bits/second) to the switching mechanism in the step-by-step central office which, when it operates, produces a 21 cps disturbance.

g. Morris points out that in choosing a coding technique for data transmission, it is not sufficient to know the line error rate and the error rate distribution. For example, in the 2/8 code, bits are transmitted in blocks of 8, and in every block there are exactly 2 marks and 6 spaces. A received block with more or less than 2 marks is detected as in error. However, even blocks with 2 errors can be detected provided they are not transpositions. Since Morris has already found that types of errors seem to predominate in groups, then transpositions are unlikely. Thus, a message using this code would experience a bit error rate of 75% during a dropout, but every one of these errors would be detected. The relative advantage of this code and of other codes of this type would go unnoticed if the codes were evaluated by a direct simulation using

field test data.

21. Performance of Data Modems.

a. The report by MITRE [27], reports their conviction that measurements of errors of modems operating over a transmission facility most often are merely measurements of circuit reliability and not the data transmission equipment.

b. Impulses seemed to be largely of 1 to 5 milliseconds in duration and were received at a level of -42 to -30 dbm (at a point where the signal level was -26 dbm). Note that the natural frequency of a telephone line centered approximately at 1.5 kc would indicate a natural response time of approximately a millisecond.

c. The MITRE investigation was also instrumented to record dropouts in addition to impulses. They found that the number per unit time of high energy level disturbances was much larger than the number of dropouts, or fades. However, the length of the disturbances due to dropouts was very much longer than the length of the disturbances due to impulses. Thus, when considering the very long time bit error rate, the circuit reliability in terms of the time magnitude of dropouts will be the limiting factor for modems operating within the speed limit of the analog channel.

d. The additional statement was made that white noise (i.e., as measured by a WE 2B set) does not seem to be a limiting factor on data transmission, using current levels; however, as the incidence of data transmissions increase, the data levels may need to be decreased in their estimation. Thus, white noise may become a factor.

22. Transmission of Data at 750 Bits/Second (England).

a. In his paper, Chittenden [28] related test results obtained in England on audio and carrier and submarine cable circuits. He used a data equipment of the phase modulated type, operating at 750 baud. His results show that short interruptions of the transmission path (which would in general be unnoticed on speech), rather than noise, are the most serious impairment with which equipment has to contend. These interruptions are very difficult to locate. In the laboratory, the receiver produced an average error rate of better than 1 wrong digit in 10^5 for a signal-to-noise ratio of +9 db over a bandwidth of 900 to 2100 cps. Since an excellent signal-to-noise ratio was available during the actual circuit testing, Chittenden concludes that, for the cases considered, the assessment of the quality of a data path, based on an average number of digit errors, is unrealistic, and that error detection with repetition is, in these circumstances, an equally effective and more efficient method of dealing with errors than is automatic (i.e., forward acting) error correction. The testing done by Chittenden was not exhaustive, but should be a reliable indicator. These results are tabulated in Figure 21.

FIGURE 21

ANALYSIS OF INTERRUPTIONS ON CARRIER CIRCUIT

SRDE - HAGUE - SRDE

Date	Period	Minutes of Test	Minute Periods Free of Errors	Nr. of Circuit Interruptions	Nr. of Errors	Duration of Longest Interruption	Duration of Shortest Interruption	Longest Error-Free Period Minutes	Shortest Error-Free Period Minutes
29.2.60 to 1.3.60	5.00 p.m. to 8.45 a.m.	945	934	4	120	78 msec	8 msec	720	1
1.3.60	9.00 a.m. to 5.00 p.m.	480	461	9	55*	120 sec	15 sec	70	2
1.3.60 to 2.3.60	5.00 p.m. to 8.45 a.m.	945	945	0	0	0	0	945	945
2.3.60	8.45 a.m. to 5.00 p.m.	495	471	7	3038	3.7 sec	18 msec	124	1

FIGURE 21 (Cont)

ANALYSIS OF INTERRUPTIONS ON CARRIER CIRCUIT

SRDE - HAGUE - SRDE

Date	Period	Minutes of Test	Minute Periods Free of Errors	Nr. of Circuit Interruptions	Nr. of Errors	Duration of Longest Interruption	Duration of Shortest Interruption	Longest Error-Free Period Minutes	Shortest Error-Free Period Minutes
2.3.60 to 3.3.60	5.15 p.m. to 8.30 a.m.	915	907	0	2368	0	0	325	1
3.3.60	9.00 a.m. to 5.00 p.m.	480	469	3	1161	0.5 sec	65 msec	251	2
3.3.60 to 4.3.60	5.00 p.m. to 8.45 a.m.	945	935	1	2618	3.5 sec	3.5 sec	580	39

* This figure does not include the errors which occurred during the disturbance lasting for 120 seconds and which it is believed was due to the application of a test tone to the circuit.

b. On Audio Circuits: The phase modulated carrier was transmitted at 0 dbm, and the 800 cps loss of the 260 mile audio frequency path was 5 db. It was noted that the general noise on the circuit was not truly random, but its level was low, of the order of -65 dbm at the receiver terminals, i.e., sufficiently low to be unimportant in this case. During an hour of observation, impulsive noise every few minutes was observed having an amplitude of about 50 mv peak-to-peak and a duration of about 2 msec. (Thus, the amplitude of the impulse peaks was still much smaller than that of the signal).

c. On Carrier and Submarine Cable Circuits: Tests were made on a 740 mile (total) path to and from The Hague. A path loss of 5 db was found. General circuit noise was of the order of -53 dbm rms (say 4 mv peak-to-peak) at the receiver terminals. During an hour of observation, impulsive noise every 10 to 20 seconds was noted, with amplitude in excess of 1 volt peak-to-peak and duration exceeding 3 msec, and also peaks of up to 800 mv with durations of 200 to 300 msec at less frequent intervals. (1 volt rms = -5 dbm).

d. Delay Distortion: Chittenden found that equalization of the delay distortion introduced by FDM carrier equipment was necessary in order to pass data. With delay distortion equalized to 1 msec from 650 to 2100 cps and using white noise, laboratory tests indicated an average digit error rate of 8 in 10^7 for a +10 db signal-to-noise ratio.

e. Interruptions: Interruptions in the continuity of the transmission path probably caused as much trouble as all other sources of interference put together, and when the number of joints (dry and otherwise) in a long circuit is considered, it is seen that there is a good possibility of a momentary disconnection somewhere or other on the route. The incidence of interruptions on The Hague circuit was much greater than on the long audio circuit due no doubt to the greater amount of apparatus, e.g., carrier equipment involved.

f. A monitor record of the level of the received signal taken on The Hague circuit enabled good correlation to be obtained between errors and interruptions, assumed to occur when there was a sudden, and often momentary, drop in the signal level. It indicated also that some of the errors were due to routine maintenance, the effects of which need not have been noticed on speech. Some of the interruptions were of the order of only a few digits long, but others were of the order of 1000 digits long. Chittenden operated a microwave Military radio relay set at about 4000 mc, well sited, over distances of 20 miles. Speech channels were provided on this radio path by a 4 channel military carrier telephone equipment and satisfactory 750 baud performance was achieved over 8 speech channels in tandem using the same radio path. When six different radio paths were put in tandem, some trouble was experienced from interruptions. Although some of these could not be accounted for, the great majority were due to deficiencies in the radio and carrier equipment which would have passed unnoticed on a circuit used only for speech.

23. SAGE Data System Tests.

a. Deriving statistical data on impulse noise is not only important in order to determine error rate, but is also needed in order to determine the type and strength of error detecting and correcting codes to use. In other words, a particular redundancy technique can be used to match the characteristics of the type of transmission medium encountered. Enticknap [29] reports that simple parity checkers were ineffective in correcting errors. However, he also states that the particular parity check device used in the test was itself unreliable. Furthermore, the block size for the parity check was varied between 16 and 256. Obviously, multiple errors will be much more frequent for such large numbers compared to an eight bit block. Finally, the conditions of the test were such that the magnitude and length of the disturbances involved are much higher than for the signal. It is evident that circuits which have been "cleaned up" will not have such calamitous noise peaks and therefore multiple errors will probably give way to single bit errors.

b. Since catastrophic degradations of hits in the form of impulse noise, dropouts, and fades are functions of the transmission medium, Enticknap feels that one should not expect any remarkable difference in the performance of various data transmission systems in terms of the overall average error rate. However, these various systems do have finegrain error characteristics due to sensitivity to level changes, frequency translation, white noise, etc.

c. Among the other things learned from this test was that a considerable period of testing, at least one month, appeared necessary to obtain a worthwhile sample of errors.

24. Impulse Noise on Telephone Circuits.

a. Yudkin [30] reports that his observations show that errors tend to occur in bursts. More exactly, data systems operate with essentially no errors most of the time; however, when errors do occur, large numbers of them occur in short periods. Private line circuits rented from AT&T Co. were tested. These included a K-carrier circuit, 200 miles long, with 11 repeaters; a TD-2 circuit, 460 miles long, with 17 repeaters, and an H-44 circuit.

b. For the H-44 circuit, a total of 158 "records" at or above 40 millivolts were observed in a total observation time of 191 hours. (A "record" is a single or multiple disturbance above a given amplitude in a half-second period.)

c. For the K-carrier, a total of 256 records at or above 20 millivolts were observed in a total observation time of 5.5 hours.

d. For the TD-2, a total of 202 records at or above 20 millivolts were observed in a total observation time of 67.75 hours.

e. The waveform of an impulse at the receiving end will depend upon the distance from where the disturbance was injected, and the delay distortion of the path. Very short impulses, injected close to the receiver, will tend to look like themselves, but if injected at some distance from the receiver, they will tend to be broadened in time and may even cause "ringing" of the line. This ringing shows up at the receiver as a finite train of sinusoids.

25. Error Rates and Distributions (England)

a. In testing data transmission over the switched telephone plant in England, Wright[31] used 50 bit blocks with the following results:

Bit Rate	Nr. of Blocks Transmitted	Nr. of Blocks In Error	Block Error Rate	Approximate Received Signal Level
250	1.5×10^5	[illegible],181	1 in [illegible]$\times 10^2$	-60 dbm
1,000	3×10^6	[illegible]	1 in 4X10[illegible]	-50 dbm
1,000	0.46×10^6	484	[illegible]	-36 dbm
1,000	1.5×10^6	[illegible]	1 in 1.6×10^3	-30 dbm

b. The error rate was quoted in terms of the data blocks in error because in a practical system data may be transmitted and errors detected on a block basis. Consequently, bursts of errors, and therefore the bit error rate, have less significance. For example, the number of wrong bits occurring during a short disconnection may equal those measured during a week in normal conditions, but the number of blocks affected will be very much lower.

c. On many connections which would be regarded as quiet, it is not unusual to find a number of isolated errors. A typical example was a case where 40,000 blocks of 50 bits resulted in 13 blocks with one error, three blocks with two errors, and two blocks with five errors. On connections where noise is recognizable, it is usual to find that errors are more concentrated and that a few blocks of 50 bits may contain 10 or even more errors. For the small percentage of connections on which noise would be regarded as a nuisance to speech, a few blocks of 50 bits may contain 20 or more errors.

B. Summary of Test Results.

1. Commercial Systems.

a. It has been found that noise on operating circuits and the resulting errors are not evenly distributed in time. The errors tend to occur in clusters or bursts or to be caused by signal drop-outs. Forward acting error correction techniques are of little use in reducing errors in these cases. Burst error correction techniques can be employed in those cases in which the signal drop-outs or error clusters are not excessively long.

b. The suggestion has been made, [32] that powerful codes could be employed where very high accuracy is needed along with reasonable cost, by only using the extra information to detect errors (and asking for a retransmission of an erroneous block). Cost is saved by not instrumenting the forward acting error correction at the receiver. Thus, since the errors tend to occur in bursts, the presence of errors is detected with high certainty compared to simple checks such as parity checkers.

c. Lerner, [33], Chittenden, [28] Enticknap, [29] and others have pointed out that substantial improvement in error rates will not be forthcoming until either the signal is designed specifically to take hits into account, or until hits are eliminated from the telephone plant. Impulse noise, dropouts, and fades, are functions of the transmission medium, but the raw digit error rate performances of the various operational data transmission systems may not show substantial differences in overall average error rate. Melas and Hopner, [9] operating in the European environment point out that switching exchanges introduce pulses onto lines, with the rotary (Strowger) switches being much worse in this respect than the crossbar switch or Ericsson switch. Morris [26] points out that where errors are predominantly either dropouts or noise bursts, proper design of the coding process will enable additional error protection over and above those predicted by coding theory on the basis of bit error rate. In this regard one may question whether the long term error rate is a definitive measure of the quality (or rather satisfactoriness) of a communications channel. (This is particularly true for communication systems assembling data by blocks. The number of wrong bits occurring during a short disconnection may equal those measured during a week in normal conditions, but the number of blocks affected may be very much lower). Since errors tend to occur in bursts, perhaps a simple error detecting code would be sufficient to identify single bit errors and the occurrence of noise bursts/dropouts would be a signal to request a repeat of that portion of the message.

d. Metzner and Morgan [32] have studied the problems accociated with the burst nature of impulse noise, and have considered the applicability of coding procedures to communications channels subject to hits, i.e., fades, circuit interruptions and noise bursts. Conventional forward acting error correcting codes are deemed inefficient because the statistics of hits are non-gaussian. i.e., they tend to occur in groups or bursts. Thus, long periods of clear transmission will be inefficiently transmitted by a coding system designed for an extremely perturbed medium. This paper suggests that these problems can be solved by employing long codes with feedback, but correcting only very small numbers of errors. By the use of long codes, while performing a minimum of forward acting error correction and stressing mere error detection, one may achieve excellent reliability in terms of maximum error rejection. The opinion is expressed that, even if the signal is lost completely, as during a deep fade, the chance of accepting a code group which is incorrect can be made negligible. Complexity of equipment is reduced by not implementing the available forward acting error correction and this is traded off against increased transmission time and the necessity for a return path.

2. Military Systems.

a. The disturbances in transmissions over military communication systems are surprisingly similar to those of commercial systems. The sources of interference and circuit configurations are in many cases different, but the observations regarding fading, error bursts, dropouts, etc. are substantially the same.

b. The Seventh Army test results emphasized the importance of personnel training in the operation and maintenance of the equipment. The "looping-back" and much of the crosstalk may have resulted from improper equipment set-up and alignment. When these difficulties were overcome, it was apparent that the data transmission capability was limited primarily by error bursts, and that during many tests the received signal was nearly error free.

c. The tests on the AN/VRC-12 indicated that impulse noise from passing vechicles was the primary source of interference and errors. It appears that this Radio Set, when properly sited and located away from heavily used roads (perhaps several hundred yards) will provide an excellent means of transmitting data. The high percentage of error-free-seconds recorded indicates that, even in the presence of an impulse noise environment, short messages can be transmitted with a high probability of error free reception.

d. The AN/PRC-25 tests indicated the basic capability of this Radio Set to transmit 75 bit per second messages. The absence of errors at this rate probably indicates an impulse-free environment. One would expect similar performance to the AN/VRC-12, although at reduced transmission rate and range.

e. The tropospheric scatter tests indicate that, on the day of the measurements, 99% or more, of all one minute messages would be received without error. It can be expected that on all but the much overdesigned tropospheric scatter circuits, performance will be poor during some days of winter. A circuit that is marginal for voice will in general be unusable for data without the use of error control techniques. Diversity reception techniques are especially beneficial in improving the quality of data transmission over tropospheric scatter circuits and should be considered a necessity in this application.

f. The tests on the AN/TCC-7 again emphasized the necessity for proper equipment alignment to improve data transmission performance. Except for the results of a thunderstorm, there was no indication in this one test that errors were "bunched". Forward error control techniques could probably be applied simply and efficiently in this case. In view of the high percentage of error free seconds (and the comparatively low average error rate) it is believed that in most applications error correction would be unnecessary.

g. The results of the H. F. Radio data transmission tests indicate that this is, perhaps, the least efficient or reliable means of transmitting data. Somewhat better performance might be expected on operational circuits since, in the test, the transmitted power was decreased when no errors occurred. In any event, the use of retransmission techniques has been shown to be an effective means of reducing error rate.

3. Implications of Test Results.

a. Error Rates and Distributions.

(1) It is doubtful if any communication system could be designed which would transmit data with an error rate of less than one error in 10^5 bits when operated for long periods of time. For instance, a circuit may operate with no errors for 23 hours, 59 minutes and 58 seconds and then have a two second outage (caused by any of an innumerable number of conditions). The average error rate for the day would be greater than 1 in 10^5! A circuit could operate for 364 days, 23 hours and 50 minutes without producing an error and then be out for 10 minutes. The average error rate would be greater than one error in 10^5 bits! It is apparent that average error rate, if it is ever considered a criterion of circuit quality, must be carefully qualified and interpreted in terms of the manner in which the errors occur. The time distribution of errors is equally, or more, important than the average error rate.

(2) The investigations quoted are in general agreement that most errors measured occur in groups, whether caused by circuit dropouts, fades, pulse interference or other man-made causes.

If the communication systems were subject only to the degradations caused by amplitude, frequency, or delay distortion, and gaussian noise, from one to three or more orders of magnitude improvement in average error rate would result.

b. Specifying the Channel.

(1) To determine the suitability of a communication channel for the transmission of digital data, one must be able to estimate the user requirements in terms of message length, speed, allowable percentage of retransmissions, and allowable undetected and detected errors per message. These estimates must be compared with estimates of the error distribution of the proposed communication channel. One must consider modification of the channel characteristics by use of error control, greater power, improved operating and maintenance techniques, better siting of radios, etc. One must further consider modification of the user requirements in light of unavoidable limitations of the communication channel. In most cases it is believed that a workable compromise among these factors can be achieved. An example of a specification of channel performance might be as follows:

"Data transmission reliability. The communication system shall be capable of transmitting messages of 1000 bit length, at an information transfer rate of 600 bits per second with the following reliability:

(a) Undetected errors. No more than one message in one thousand shall be received with any undetected errors.

(b) Detected errors. No more than one message in one hundred shall be received with uncorrectable errors after a maximum of two retransmissions. (It is assumed that messages received with detected (but uncorrectable) errors will be retransmitted and that if the retransmitted message is received with detected (but uncorrectable) errors it will be retransmitted once again.)"

(2) A specification of the transmission channel is believed to possess the advantages of accurately reflecting the user's requirement to

(a) seldom receive an incorrect message and believe it to be correct,

(b) minimize the number of retransmissions necessary to receive an error free message, and

(c) to specify a minimum rate of information transfer. This specification will allow the communication system designer to evaluate a proposed transmission facility by examining the likelihood of an error or errors occurring within the duration of a message, by investigating the use of error control techniques, etc.

c. Error Control Techniques.

(1) It is apparent the error control is necessary to avoid the acceptance of erroneous messages and may be desirable to improve the transmission channel performance. Error detection techniques[34], of modest complexity, are known which can reduce the probability of receiving and accepting a message with an undetected error to one chance in 10^6, or 10^{10}, or 10^{30} for that matter. The power of this technique can be seen when we calculate that if this probability is set at 10^{-12}, and assume a bit rate of 1200 bits per second, we would expect to receive one undetected error in 30 years of continuous transmission. In general no more than a 50% reduction in information rate (often less) is required in applying this technique.

(2) Forward error correction techniques may also be valuable in matching the communication channel to the data transmission requirement. No more than 50% redundancy [35] is required in most cases. When both error correction and detection are used, the reduction in information transfer rate would be less than 75%, since the error correcting equipment would significantly decrease the number of message retranmissions required. Burst error correction seems especially important in view of the experimental results previously reported. In any case the need for error correction, the type of error correction, and its effectiveness are strongly dependent on the data transmission requirement and the communication channel under consideration [36]. While error detection and retransmission appear mandatory in most cases, error correction can be said only to be desirable under specific conditions.

4. Future Testing.

a. Although the available information regarding data transmission quality over various communication channels is extensive, there is no doubt that more information is required. These tests fall into three general categories. An evaluation of the basic performance limitations of the transmission channels is necessary. Data is needed to determine methods of improving this performance. A verification of estimated performance of specific data systems operating through specific communication channels is required.

b. Evaluation of Channel Performance Limitations.

(1) It is in this category that the most experimental data is available. Additional information in this area is needed mainly for new equipments as they are introduced into the Army, and for equipments to be operated in environments and configurations differing from those under which previous tests were performed.

c. Tests to Determine Methods of Improving Channel Performance.

(1) It has previously been noted that circuit downtime has frequently been the result of faulty operating and maintenance procedures. These difficulties must be clearly identified and eliminated if satisfactory performance is to be assured. Examples of these problems are the "loop-back" and crosstalk found during the Seventh Army tests as well as misalignment of multiplex and radio sets. It is probable that, as a result of these investigations, a list of precautions and procedures unique to data transmission will be generated.

(2) While the above problems are presumably operator caused, there is no doubt that the communication equipment shortcomings contribute to less-than-optimum data transmission performance. Additional investigations into these causes may lead to improvements in both the issued equipments and in equipments now in development.

(3) The application of error correction techniques must be carefully evaluated in terms of the data transmission requirement and the error statistics of the channel. It is in this area that the least data is available in the desired form and under the necessary conditions. The collection of useful data is hampered by a lack of knowledge of user requirements. In general channel error statistics must be reduced before recording in order to minimize the storage, handling and further processing of the quantities of data involved. To avoid discarding that information which will later prove to be most significant, the experimenter must know what to look for. What he looks for depends on both his familiarity with error correction equipment and techniques and his knowledge of user requirements (in terms of message length, rates, etc.). It is clear that experiments to determine the design of error correction equipments must be performed on specific communication channels with a firm understanding of what is desired of that channel.

d. Verification of Specific Data/Communication Systems.

(1) Because of the complexity and interdependence of the data processing system and the communication system they should be tested together as early as possible in their development. These tests should be performed under a realistic field environment by operating personnel. Sources of interference should be anticipated. These sources must be included in the tests. It is believed that these tests would reveal necessary modifications in operating procedures, would clarify the requirements of the data processing techniques, and would provide a firm basis for further optimization of the combined systems.

IV. CONCLUSIONS

1. Although the probability of reception of messages with errors can not in any realistic situation be reduced to zero, each communication channel tested has the capability of transmitting data. Under certain conditions the performance of HF and scatter circuits must be considered poor. Radio relay, cable, and wire lines generally perform excellently.

Other systems such as VHF radio seem to vary in performance, depending on the environment and application.

2. In most cases errors appear in clusters. They may be caused by operator mistakes, faulty maintenance, equipment failures, interference, propagation effects, background noise, etc. The average error rate is a less descriptive and less important quantity than the time distribution of errors.

3. The communication channel should, and can, be specified in a manner which both clearly reflects the data user requirements and accurately describes the engineering goal of the communication system designer. The quantities to be considered include message length, information transfer rate, allowable undetected and detected errors, retransmission capability, etc.

4. Error detection and retransmission must be considered as prime techniques to be used in data transmission systems. Error detection codes exist which can virtually eliminate the possibility of unknowingly accepting an erroneous message. Forward error correction may be useful in optimizing the communication system for data; the specific data/communication system must be carefully examined to determine the applicability of error correction.

5. Additional testing is required in the following areas:

a. Evaluation of channel performance. Additional information is needed in this area mainly for new equipments as they are introduced into the Army and for existing equipments operating in new environments.

b. Tests to determine methods of improving performance. The causes of errors can often be located through testing and eliminated. To design error control equipment, the channel statistics must be known.

c. Verification of specific data/communication systems. The inter-operation of these systems must be tested early in their development so that unforeseen troubles can be identified and corrected, operating procedures can be established, and a firm assurance made that the overall objectives are met by the systems.

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ACKNOWLEDGEMENTS

The contributions to this report by the following individuals are gratefully acknowledged:

J. R. Tucker	- AN/VRC-12 and An/TCC-7 tests.
K. Way	- Collected test results as reported in reference 37.
M. Baltas	- Extensive literature research and interpretation, reference 38.
B. Goldberg	- HF Radio tests.
J. Dressner	- UNICOM tests.
A. Gillette	- Seventh Army Tests.
C. Q. Murphy	- Data reduction and interpretation.